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EFFECT OF HEAT AND POWER EXTRACTION ON TURBOJET-ENGINE PERFORMANCE

III - ANALYTICAL DETERMINATION OF EFFECTS OF SHAFT-POWER EXTRACTION

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Lewis Flight Propulsion Laboratory
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SUMMARY

The performance of an axial-flow-type turbojet engine operating with shaft-power extraction was analytically determined by matching experimentally determined component characteristics of a typical axial-flow-type engine. Performance is presented in the form of generalized working charts that were used to investigate engine performance with variable and rated tail-pipe-nozzle area operation at constant turbine-inlet temperature, constant engine speed, and constant thrust. A range of altitudes and flight Mach numbers was considered. The maximum power extraction permissible is presented as a function of altitude and thrust.

For operation at a given altitude, extracting a given amount of shaft power caused greater performance penalties at low turbine-inlet temperatures than at high turbine-inlet temperatures. The performance penalty due to extracting a given amount of shaft power increased with increasing altitude.

INTRODUCTION

In the operation of aircraft, large quantities of heat and power may be needed for auxiliary purposes. The maximum amount of energy necessary for these purposes will probably be required only for small portions of the total flight time; consequently, auxiliary sources used to supply this energy will seldom operate at full capacity. As the auxiliary equipment will occupy space and pay-load capacity during the entire flight, an evaluation of schemes for obtaining energy with a minimum of auxiliary equipment is desirable. An obvious method of minimizing the required auxiliary equipment is to derive the desired energy from the aircraft power plant. An analytical project for evaluating and comparing the effects of various methods of energy extraction on the performance of a turbojet engine is therefore in progress at the NACA Lewis laboratory. The initial phase of this investigation, the evaluation of engine performance with air bled from the compressor outlet, is presented in references 1 and 2. The effect of shaft-power extraction on the performance of a typical axial-flow-type turbojet engine is evaluated herein. 1397

The generalized engine performance, calculated by matching experimentally determined component characteristics of a typical turbojet engine, is presented in the form of working charts. Performance under several representative modes of engine operation is calculated from these charts. In these calculations, the effects of such variables as engine speed, turbine-inlet temperature, engine-inlet temperature, flight Mach number, and altitude are evaluated. Data are presented to show the engine performance with shaft-power extraction at constant thrust levels and the maximum permissible shaft-power extraction as a function of thrust level and altitude. Operation with both variable and constant tail-pipe-nozzle area is considered.

SYMBOLS

The following symbols are used in this analysis:

A area, square feet

F_n net thrust, pounds

ΔH enthalpy change, Btu per pound

hp horsepower

Δhp horsepower extracted

N engine speed, rpm

P total pressure, pounds per square foot absolute

p static pressure, pounds per square foot absolute

T total temperature, $^{\circ}R$

W_a air flow, pounds per second

W_f fuel flow, pounds per hour

ΔW_f difference in fuel flows with and without power extraction at same thrust level

δ ratio of total pressure to NACA standard sea-level pressure, P/2116

θ ratio of total temperature to NACA standard sea-level temperature, T/519

Subscripts:

0 free stream

1 diffuser inlet

2 compressor inlet

3 compressor outlet

4 turbine inlet

5 turbine outlet

6 tail-pipe nozzle

c compressor

r rated value or value obtained when operating with NACA standard sea-level static inlet conditions at rated engine speed and rated turbine-inlet temperature

t turbine

Superscript:

' value at zero power extraction, rated turbine-inlet temperature, rated engine speed, and particular NACA standard flight condition considered

PRESENTATION OF WORKING CHARTS

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The performance of an axial-flow-type turbojet engine operating with shaft-power extraction is presented in the form of generalized working charts in figures 1 to 6. These working charts were calculated from pumping characteristics of a basic turbojet engine operating with shaft-power extraction. The pumping characteristics were obtained by matching the experimentally determined component characteristics of a typical axial-flow-type turbojet engine in a manner similar to that used in reference 1. In the present case, the matching procedure involved a change in the power parameter of the turbine relative to that of the compressor instead of a relative change in the mass-flow parameters of the compressor and the turbine, as was used in reference 1. The component characteristics used in the analysis and an explanation of the method of analysis are presented in appendix A.

A power-extraction factor $\dfrac{\Delta hp/\delta_2\sqrt{\theta_2}}{\left(hp/\delta_2\sqrt{\theta_2}\right)_{r,c}}$ is used as the abscissa throughout the working charts. This factor represents the ratio of the corrected horsepower extracted from the shaft of the engine to the compressor horsepower at sea-level rated conditions. Corrected net thrust F_n/δ_2, expressed as a fraction of its rated value, is used as a parameter in all charts.

The performance of the engine operating with shaft-power extraction at a ram pressure ratio of 1.35 is presented in figures 1 to 3. An inlet-diffuser total-pressure loss equal to 8 percent of the ram-pressure rise is incorporated in the charts. Parts (a), (b), and (c) of figures 1 to 3 represent operation at corrected engine speeds $N/\sqrt{\theta_2}$ of 0.9, 1.0, and 1.1 rated engine speed, respectively. The turbine-inlet temperature ratio T_4/T_2 and the tail-pipe-nozzle area A_6 are shown in figures 1 and 2, respectively. Both quantities are presented as fractions of their sea-level rated values.

In figure 3, the specific fuel consumption $W_f/F_n\sqrt{\theta_2}$ is presented as a fraction of its rated value, and the equivalent power-extraction specific fuel consumption $\Delta W_f/\Delta hp$ (computed by charging the entire increase in fuel consumption to the power extraction) is presented as pounds of fuel consumed per hour per horsepower extracted from the shaft. Because all quantities except $\Delta W_f/\Delta hp$ are shown as fractions of rated values, the rated value of the compressor pressure ratio $(P_3/P_2)_r$ has only second-order effects on these quantities. The factor $\Delta W_f/\Delta hp$ is an absolute quantity, however, and its value is directly affected by the rated value of the compressor pressure ratio. The equivalent power-extraction specific fuel consumption is presented in figure 3 for $(P_3/P_2)_r$ of 4.0. For values of rated compressor pressure ratio from 4.0 to 5.0, the value of $\Delta W_f/\Delta hp$ decreases by approximately 0.8 of the percentage increase in $(P_3/P_2)_r$.

The performance of the engine operating with shaft-power extraction at static inlet conditions (ram pressure ratio, 0.99) is presented in figures 4 to 6. These figures exhibit the same trends as figures 1 to 3 and are applied in a similar manner.

An example illustrating the method of using the working charts is presented in appendix B.

LIMITATIONS OF WORKING CHARTS

Inasmuch as the present analysis is based on the component characteristics of a particular engine, the accuracy of performance prediction for an engine of different design would depend on the similarity between the component characteristics of that engine and the engine used in computing the working charts, and consequently on the similarity of the pumping characteristics of the two engines. Although no experimental data are available for axial-flow-type engines operating with shaft-power extraction, an indication of the generality of this type analysis and its applicability to other engines is given in reference 1 in which analytical and experimental air-bleed data from engines of different design are compared. Good agreement between the analytical and the experimental data was obtained in spite of the difference in engine design. The same component characteristics and method of matching are used in both the air-bleed and the shaft-power analyses; therefore it is expected that the present analysis is applicable to axial-flow-type engines other than the one on which it is based.

Although the pumping characteristics of two engines may show excellent agreement, the same agreement between the thrust and the specific-fuel-consumption parameters for the engines does not necessarily occur. These performance factors may fail to check because of differences in the operating levels of the engines, as is evident from unequal temperature and pressure ratios at rated engine conditions. The effect of departures in the engine operating level from the values used in the analysis was therefore investigated.

For rated compressor pressure ratios from 4 to 5 and rated turbine-inlet temperatures from 1800° to 2000° R, the values of the thrust and the specific fuel consumption could be predicted within 3 percent for ram pressure ratios from 1.2 to 1.6 from figures 1 to 3 and for static conditions from figures 4 to 6. For ram pressure ratios between 1.0 and 1.2, the absolute values of the thrust and the specific fuel consumption could not be predicted to as high a degree of accuracy; the percentage change in these factors due to power extraction, however, is relatively constant for ram pressure ratios from 1.0 to 1.6. The percentage changes in thrust and specific fuel consumption due to power extraction can therefore be predicted for the ram pressure ratio range of 1.0 to 1.2 by the use of the static-performance charts (figs. 4 to 6).

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Although the working charts presented herein may not be applicable to centrifugal-flow-type engines or to axial-flow-type engines operating out of the range of compressor pressure ratios from 4 to 5 and turbine-inlet temperatures from 1800° to 2000° R, the method of analysis (appendix A) is general and may be applied to any engine regardless of type or level of operation if component performance characteristics are available.

CALCULATION AND PRESENTATION OF RESULTS

Calculation of engine performance under specific modes of engine operation was accomplished with the aid of the working charts of figures 1 to 6 in a manner similar to that of reference 2. If any two of the quantities on the working charts are known, the other performance variables are easily obtained. Thus, for a given flight condition at which the temperature and the pressure at the engine inlet are known, net thrust, specific fuel consumption, and tail-pipe-nozzle area can be determined for any desired engine speed, turbine-inlet temperature, and power extraction within the limits of the charts. Because the working charts are presented for only three corrected engine speeds, interpolation is necessary for intermediate speeds. This interpolation is not linear and greater accuracy in calculation can be obtained by cross-plotting the variables against corrected engine speed for constant values of corrected thrust and power extraction.

The effects of shaft-power extraction on various specific modes of engine operation are presented as functions of an uncorrected power-extraction factor $\Delta hp/(hp)_r$. In presenting these effects, the various engine performance parameters are expressed as fractions of a reference value. The reference value is taken as the value of the variable with zero power extraction, rated turbine-inlet temperature, and rated engine speed at the particular standard flight condition considered. A choice of reference conditions such as this one was necessary inasmuch as the component characteristics on which the analysis in appendix A is based are idealized for all flight conditions, and such factors as the effect of changing Reynolds number with altitude are not considered. Although variations in Reynolds number have a direct (although small) effect on the magnitude of the engine variables, the effect of such variations on the changes in the engine variables with power extraction is negligible.

Effect of Engine Speed and Turbine-Inlet Temperature

The performance of a turbojet engine operating with shaft-power extraction at rated turbine-inlet temperature, an altitude of 20,000 feet, and a flight Mach number of 0.7 is presented in figure 7(a). Curves are given for three modes of engine operation: variable area at rated engine speed and at 0.93 rated engine speed and rated tail-pipe-nozzle area operation with variable engine speed. Rated engine speed corresponds to maximum power operation and 0.93 rated engine speed corresponds approximately to minimum specific-fuel-consumption operation.

It is apparent from figure 7(a) that approximately the same thrust and specific fuel consumption were obtained for all three modes of engine operation. For a power-extraction factor of 0.04, the thrust decreased approximately 5 percent and the specific fuel consumption increased approximately 4 percent from the values with no power extracted. At higher values of power extraction, the thrust obtained with rated-area operation began to decrease more rapidly. In general, slightly lower values of both thrust and specific fuel consumption were obtained at 0.93 rated speed than at rated speed. The variation of engine speed and tail-pipe-nozzle area are also shown on figure 7(a).

In figure 7(b), the performance of a turbojet engine operating at 0.9 rated turbine-inlet temperature is shown for the same flight conditions as figure 7(a). Again operation with variable area at rated and 0.93 rated engine speeds and operation with rated tail-pipe-nozzle area are considered. At a power-extraction factor of 0.04, the thrust decreased and the specific fuel consumption increased approximately 7 percent from the values for zero power extraction. Although the performance with the different modes of operation is essentially the same at low power extractions, greater decreases in thrust result for the rated-area than for variable-area operation at high power extractions. This larger decrease in thrust is caused by the reduction in engine speed (and air flow) that is necessary in order to maintain a constant turbine-inlet temperature with the constant-area operation. This trend indicates the desirability of a variable-area tail-pipe nozzle if large power extractions are contemplated.

A comparison of figures 7(a) and 7(b) indicates that for the same amount of power extraction the greater performance penalties are obtained at the lower turbine-inlet temperature operation. These results are consistent with those of reference 2, which show by means of a simplified cycle analysis that the extraction of energy from a turbojet-engine cycle at low values of turbine-inlet temperature ratio results in greater performance penalties than extraction at high values.

Effect of Engine-Inlet Temperature

The effect of engine-inlet temperature on the performance of an engine operating with shaft-power extraction at static sea-level conditions is shown in figure 8. The engine-inlet temperatures 99°, 59°, and 20° F correspond to sea-level static operation with Army summer air, with NACA standard air, and under icing conditions, respectively. Rated turbine-inlet temperature operation at both rated engine speed and rated tail-pipe-nozzle area is considered.

Increasing the engine-inlet temperature from 20° to 99° F caused a decrease in thrust for both variable- and constant-area operation for all values of power extraction. At the low temperatures and at low power extractions for the highest temperature, little difference is shown between operation with variable and rated tail-pipe-nozzle area. For a power-extraction factor of 0.04, the thrust decreases approximately 2, 3, and 4 percent for operation at compressor-inlet temperatures of 20°, 59°, and 99° F, respectively. This variation was to be expected because, for constant turbine-inlet-temperature operation, increasing the engine-inlet temperature decreases the turbine-inlet temperature ratio. As previously stated, extracting power at low turbine-inlet temperature ratios results in larger changes in engine performance. For variable-area operation, more than 10 percent of the rated compressor horsepower can be extracted from the shaft of the engine in NACA standard air before the thrust decreases to the value obtained with zero power extraction in Army summer air.

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Mach Number Effect

The effect of flight Mach number on the performance of an engine operating under the same modes as those in figure 8 is shown in figure 9 for an altitude of 20,000 feet and a power-extraction factor of 0.04. As previously discussed, the working charts of figures 1 to 3 are applicable to ram pressure ratios of 1.2 to 1.6. The performance over the corresponding range of flight Mach number, approximately 0.55 to 0.85, is therefore affected only by changes in inlet temperature and pressure with ram. The data indicate that in this range of flight Mach number the effect of changes in flight Mach number is very small.

Altitude Effect

The effect of altitude on engine performance for a flight Mach number of 0.7, rated turbine-inlet temperature, and an uncorrected power-extraction factor $\Delta hp/(hp)_{r,c}$ of 0.04 is shown in figure 10. Similar curves would be obtained for other power extractions. A comparison is made between operation at rated engine speed and operation with rated tail-pipe-nozzle area.

Figure 10 indicates that extracting a given amount of power at various altitudes results in greater decreases in thrust and increases in specific fuel consumption at high altitude than at low altitude. This net change in the cost of power removal with altitude is the result of two counteracting factors: At a given turbine-inlet temperature, increasing the altitude increases the turbine-inlet temperature ratio. Increasing this ratio tends to reduce the effects of a given percentage of shaft-power extraction on the engine performance. Because of the large decrease in mass flow with increase in altitude, however, the compressor power decreases considerably. Therefore, extraction of a given amount of power from the shaft at increasing altitude results in extraction of greater percentages of the compressor power and consequently causes greater changes in engine performance.

At high altitude, slightly lower thrust and higher specific fuel consumption were obtained with variable-area operation than with rated-area operation because, at a given turbine-inlet temperature ratio, corrected engine speeds exist at which the thrust and the specific fuel consumption are a maximum and a minimum, respectively. For high-altitude operation with rated engine speed and variable area, the corrected engine speed was beyond the optimum for both thrust and specific fuel consumption. For constant-area

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operation, the engine speed was reduced to prevent exceeding rated turbine-inlet temperature, thereby approaching the corrected engine speeds for optimum thrust and specific fuel consumption. High-altitude performance with the variable tail-pipe-nozzle area could be improved by decreasing engine speed.

For rated tail-pipe-nozzle area operation, the area ratio A_6/A_6' decreased slightly with increasing altitude because A_6', the area necessary to maintain rated turbine-inlet temperature at rated engine speed and zero power extraction, increased with altitude.

Constant-Thrust Operation

At a given altitude, in order to maintain constant flight velocity, constant thrust must be maintained. The effect of extracting power from the shaft of a turbojet engine while maintaining constant thrust at an altitude of 20,000 feet and a flight Mach number of 0.7 is shown in figure 11. The thrust is held at 80 percent of the thrust obtainable at zero power extraction, rated turbine-inlet temperature, and rated engine speed. Two modes of engine operation are presented; variable tail-pipe-nozzle area at rated engine speed and rated area with variable speed.

In order to maintain constant thrust at a power-extraction factor of 0.04, it is necessary to increase the turbine-inlet temperature approximately 4 percent above the zero power-extraction value for both the variable-area, constant-speed operation and the rated-area, variable-speed operation. Slightly lower specific fuel consumption is obtained with the rated tail-pipe-nozzle area engine inasmuch as it is operating more nearly at cruise engine speed. At a power-extraction factor of 0.04, the specific fuel consumption increases approximately 7 percent from the value with no power removed for both modes of engine operation.

Maximum Permissible Power Extraction

The maximum permissible shaft-power extraction for variable and rated tail-pipe-nozzle area operation while maintaining a given amount of thrust at rated turbine-inlet temperature and various altitudes is presented in figure 12. The variable-area operation is at rated engine speed; the rated-area operation is at variable speed.

While operating at a given thrust at low altitude, more power can be removed with variable-area operation than with rated-area operation. This effect is especially pronounced at low values of thrust. For example, at a fraction of rated net thrust F_n/F_n' of 0.92, 36 percent more power can be extracted at sea level with variable-area operation at rated engine speed than with rated-area operation. At higher altitudes, however, the curves cross over and more power can be obtained with the rated-area operation than with variable-area operation at rated engine speed. Greater amounts of power could be obtained with variable-area operation at high altitude by reducing the engine speed because the corrected engine speed at high altitude is beyond the optimum for maximum power extraction.

CONCLUDING REMARKS

The performance of an axial-flow-type turbojet engine operating with shaft-power extraction is presented in the form of generalized working charts. These charts are applicable to a wide range of operating conditions for engines with rated compressor pressure ratios in the range from 4 to 5 and rated turbine-inlet temperatures from 1800° to 2000° R. The method of analysis is applicable to any engine, with a centrifugal- or axial-flow-type compressor, in any range of compressor pressure ratios and turbine-inlet temperatures.

For operation at a given altitude, extraction of a given amount of shaft power caused greater performance penalties at low turbine-inlet temperature than at high turbine-inlet temperature. The performance penalties resulting from removal of a given amount of shaft power increased with increasing altitude. Varying the flight Mach number from 0.55 to 0.85 while removing a given amount of shaft power had no appreciable effect on the performance penalties. Increasing the engine-inlet temperature increased the performance penalty caused by a given shaft-power extraction.

At low values of shaft-power extraction, engine performance was impaired to about the same extent whether the engine was operated with a variable-area nozzle or a rated-area nozzle. At high power extractions, use of the variable-area nozzle generally resulted in higher thrust and lower specific fuel consumption.

The amount of power that can be removed decreased as the altitude was increased. At low altitudes, more power could be removed when the engine was operated with a variable-area nozzle than with a rated-area nozzle.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, May 12, 1950.

APPENDIX A

DEVELOPMENT OF ANALYSIS

The performance of a basic turbojet engine operating with shaft-power extraction was determined by matching the experimentally determined component characteristics of a typical axial-flow-type turbojet engine. The performance of the complete propulsion system was determined by use of the characteristics of the basic engine, the engine-inlet system, and the tail-pipe nozzle.

Basic Engine Performance

<u>Matching procedure.</u> - The process of determining the performance of a compressor and a turbine operating as a single unit from established characteristics of the individual components is known as matching. The components are considered matched when a given relation exists between rotational speed, mass flow, and enthalpy change of the compressor and the corresponding factors for the turbine. The matching points are determined in the following manner by using the method of reference 3: From altitude-wind-tunnel investigations of a complete axial-flow-type turbojet engine with several different tail-pipe-nozzle areas, component characteristics were obtained for a range of altitudes and flight Mach numbers. A set of idealized component characteristics was obtained by fairing a single curve through data points for several flight conditions. The idealized compressor characteristics are presented in figure 13. The corrected compressor mass flow $W_{a,c}\sqrt{\theta_2}/\delta_2$ is presented as a function of the corrected engine speed $N/\sqrt{\theta_2}$. Also, the relation between the compressor power parameter $W_{a,c}\Delta H_c/N\delta_3$ (called torque parameter in reference 3), the compressor mass-flow parameter $W_{a,c}N/\delta_3$, and the corrected compressor speed $N/\sqrt{\theta_3}$ is shown. All quantities are given as fractions of sea-level rated values.

In a similar manner, the idealized turbine characteristics are presented in figure 14. The turbine pressure ratio P_4/P_5 is presented as a function of the turbine temperature ratio T_4/T_5. The turbine power parameter $W_{a,t}\Delta H_t/N\delta_4$ is presented as a function of the turbine mass-flow parameter $W_{a,t}N/\delta_4$ and the corrected turbine speed $N/\sqrt{\theta_4}$.

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Assuming a pressure ratio across the combustion chamber ($\delta_4 = 0.945\ \delta_3$) allows the power and the mass-flow parameters of both compressor and turbine to be corrected to the same pressure and thus plotted on the same plane. For steady-state operation, the compressor and the turbine mass-flow parameters are equal inasmuch as W_a and N for the compressor are equal, respectively, to W_a and N for the turbine. The enthalpy change of the fuel mass flow passing through the turbine was assumed equal to the bearing and accessory losses. For steady-state operation with zero power extraction, the power developed by the air passing through the turbine must therefore be equal to the power absorbed by the compressor. Consequently, the compressor and turbine power parameters are equal for a matched condition. Operating points of the compressor-turbine combinations can be obtained by superimposing the component characteristics. The matching chart resulting from the superposition of the component characteristics is shown in figure 15.

When power is being extracted from the shaft of a turbojet engine, the turbine not only has to supply the power absorbed by compressor, bearings, and accessories but also the power that is being extracted from the shaft. Because the enthalpy change of the fuel passing through the turbine was assumed equal to the bearing and accessory losses, the total enthalpy change of the air passing through the turbine is greater than that across the compressor by the amount of power that is being extracted. In order to take this relation into account on the matching chart, the entire turbine grid is shifted downward by the amount of power that is being removed. Inasmuch as the lines of constant corrected turbine speed on the turbine grid are vertical, the only apparent change in the matching chart due to a downward shift of the turbine grid is the shifting of the turbine ordinate or power parameter. The turbine power-parameter scale corresponding to a power extraction of 2 percent of the compressor power at any point on the matching chart is shown in figure 15. Thus, at any point on the matching chart, the turbine power parameter for this power extraction is equal to 102 percent of the compressor power parameter.

Every point on the matching chart defines a possible operating point of the engine. By the proper algebraic manipulation of the information on the chart, as discussed in reference 1, along with the remainder of the component-characteristics curves, the pressures and the temperatures throughout the engine can be calculated. Engine performance with various amounts of power extraction can be calculated by shifting the turbine characteristics in the proper manner for each power extraction.

Over-all pumping characteristics. - The performance of the basic turbojet engine, as determined by the matching procedure, is presented in the form of pumping characteristics by using the method of reference 4. The basic engine is considered as a pump consisting of compressor, combustion chamber, and turbine, the purpose of which is to raise the temperature and the pressure of the fluid passing through it. The pumping characteristics consist of a curve of engine pressure ratio as a function of engine temperature ratio, power extraction, and corrected engine speed, and a curve of corrected engine mass flow as a function of corrected engine speed (identical with the compressor mass-flow characteristics, fig. 13). The relation between engine pressure ratio and engine temperature ratio is presented in figure 16 for shaft-power extraction of 0, 5, 10, and 15 percent of the actual compressor horsepower for corrected engine speeds of 0.9, 1.0, and 1.1 rated engine speed. The variation of turbine-inlet temperature ratio and compressor-outlet temperature ratio are similarly shown in figures 17 and 18, respectively. All quantities are presented as fractions of rated values.

Propulsion-System Performance

The complete propulsion system consists of a basic turbojet engine with an engine-inlet system and a tail-pipe nozzle. The performance of the complete system is determined by combining the characteristics of the inlet system and the tail-pipe nozzle with the characteristics of the basic engine.

For a given flight Mach number and inlet-diffuser loss, the tail-pipe-nozzle area necessary to operate at any point on the curves of figure 16 and the thrust produced by operation at any point are determined from one-dimensional flow relations. The fuel-air ratio is computed from reference 5 using the temperature ratio across the combustion chamber T_4/T_3, obtained from figures 17 and 18. The specific fuel consumption is computed using fuel-air ratio, engine mass flow, and engine net thrust. A more complete description of the method of computing the propulsion-system performance is presented in reference 1.

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APPENDIX B

USE OF PERFORMANCE CHARTS

The use of the working charts (figs. 1 to 6) in solving performance problems is illustrated by the following example: A hypothetical engine, similar to current axial-flow-type engines, has the following characteristics at rated sea-level operation:

F_n/δ_2, lb	4000
$N/\sqrt{\theta_2}$, rpm	10,000
$W_f/F_n\sqrt{\theta_2}$, lb/(hr)/(lb thrust)	1.0
A_6, sq ft	1.215
T_4, $^{\circ}$R	1870
P_3/P_2	4.0
$(hp/\delta_2\sqrt{\theta_2})_{r,c}$, hp	6000

The engine is to operate at rated corrected engine speed at an altitude of 20,000 feet and a flight Mach number of 0.7. The drag characteristics of the plane are such that a corrected thrust F_n/δ_2 of 2000 pounds is required to maintain this flight condition. The airplane requires an auxiliary power supply of 500 horsepower.

From the flight conditions, inlet characteristics used in the analysis $\left[\frac{P_2}{p_0} = 1 + 0.92\left(\frac{P_1-p_0}{p_0}\right)\right]$, and values of the standard atmosphere obtained from reference 6, the following values were obtained:

P_2/p_0	1.352
P_2, lb/sq ft	1315
T_2, $^{\circ}$R	492
δ_2	0.623
θ_2	0.948

Inasmuch as the ram pressure ratio falls within the range of 1.2 to 1.6, figures 1 to 3 are applicable. Because the engine is operating at rated corrected engine speed, figures 1(b), 2(b), and 3(b) should be used.

In order to use the charts, the thrust parameter $\frac{F_n/\delta_2}{(F_n/\delta_2)_r}$ and the power-extraction factor $\frac{\Delta hp/\delta_2\sqrt{\theta_2}}{(hp/\delta_2\sqrt{\theta_2})_{r,c}}$ must be evaluated. The thrust parameter is simply the required corrected thrust of 2000 pounds divided by the rated thrust of 4000 pounds, or 0.5. The power-extraction factor is evaluated as follows:

$$\frac{\Delta hp/\delta_2 \sqrt{\theta_2}}{(hp/\delta_2 \sqrt{\theta_2})_{r,c}} = \frac{500/(0.623)(\sqrt{0.948})}{6000} = 0.1375$$

The remainder of the performance parameters are obtained from figures 1 to 3. The values are given in the following table in both fractional and absolute form:

$\frac{T_4/T_2}{(T_4/T_2)_r}$	0.874
T_4, ^{o}R	1548
$A_6/(A_6)_r$	1.238
A_6, sq ft	1.508
$\frac{W_f/F_n \sqrt{\theta_2}}{(W_f/F_n \sqrt{\theta_2})_r}$	1.547
W_f/F_n, lb/(hr)(lb)	1.505
$\frac{\Delta W_f}{hp}$, lb/(hr)(hp)	0.61

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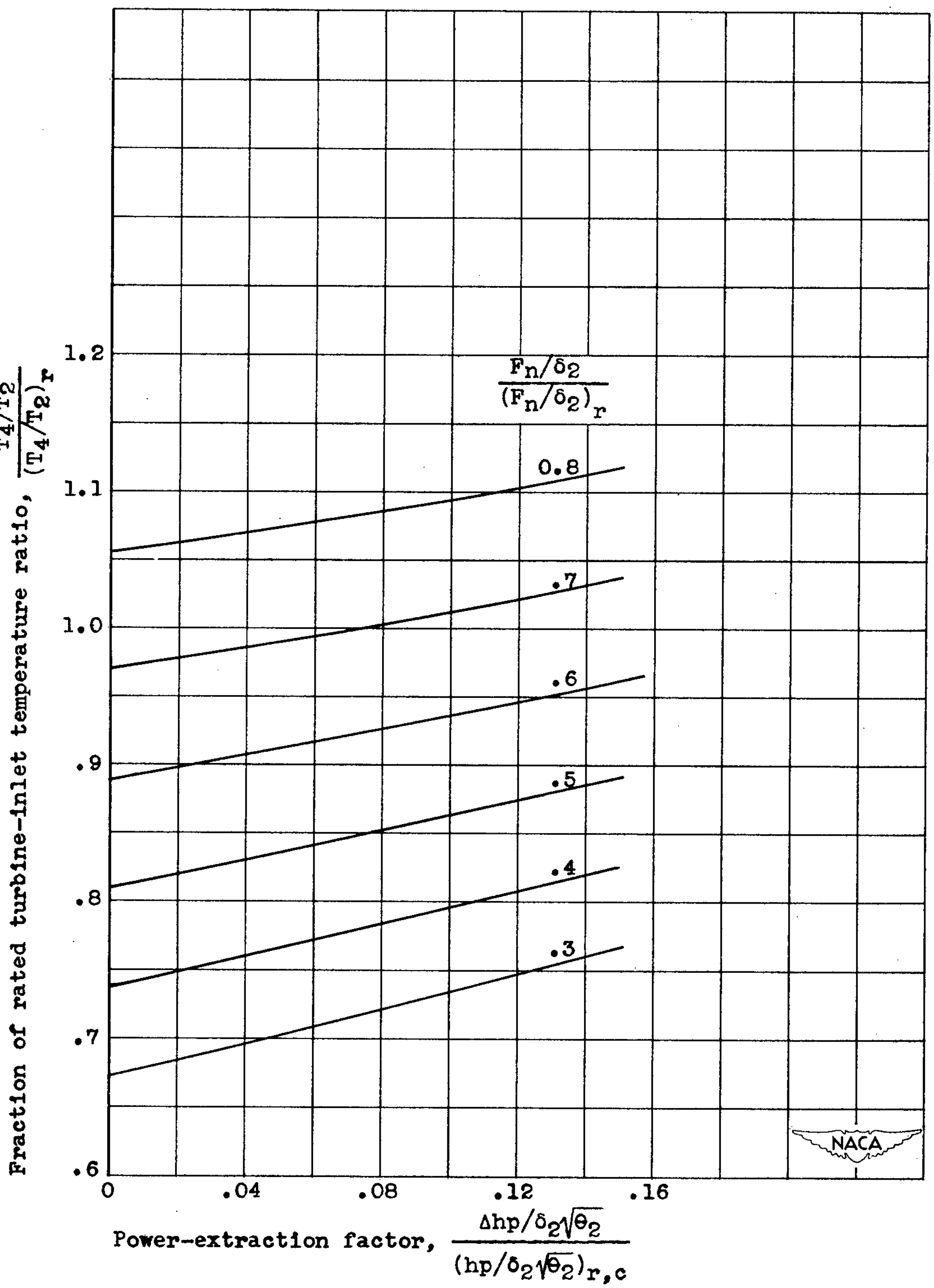
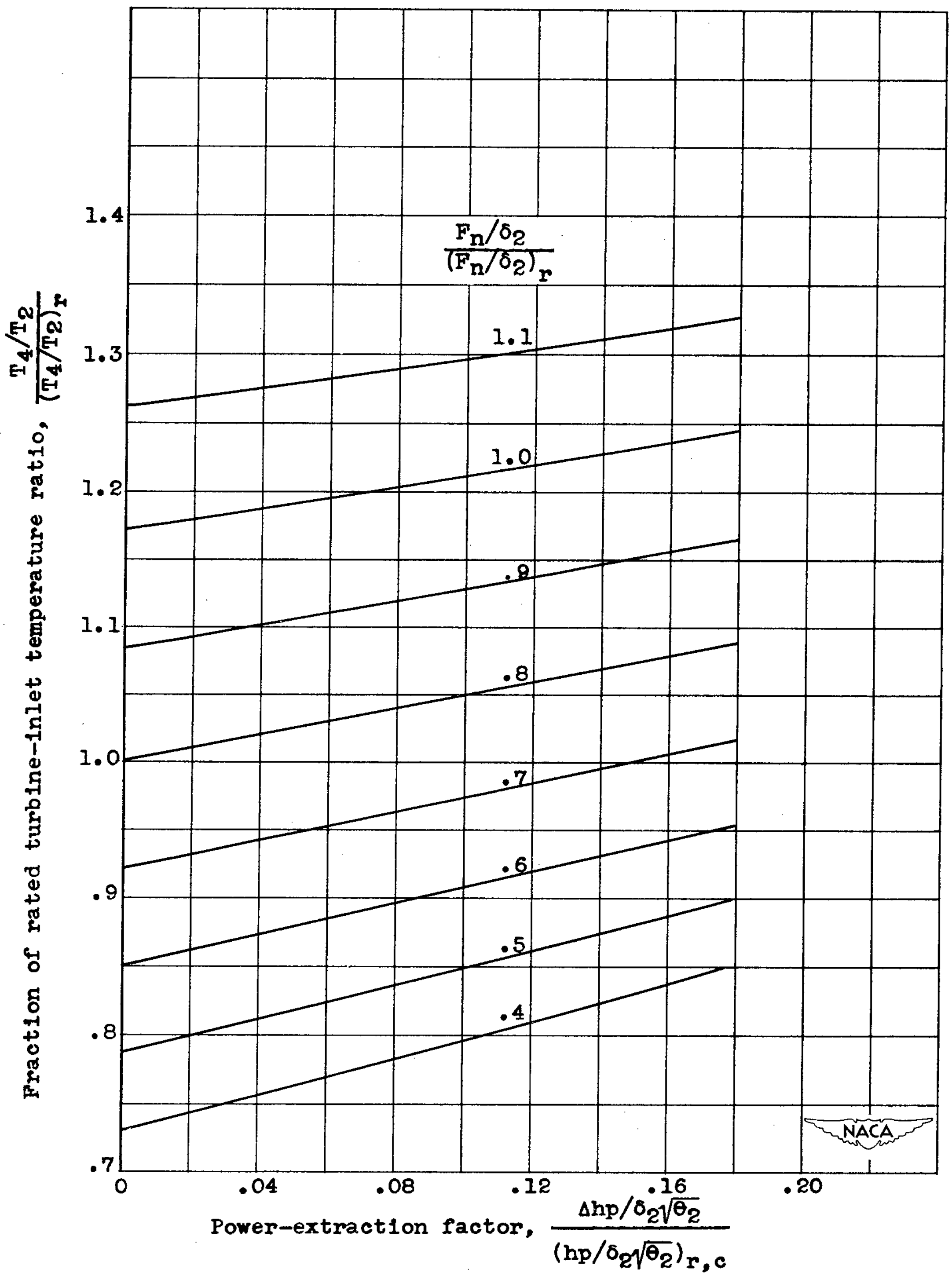


(a) Corrected engine speed, 0.9 rated.

Figure 1. - Variation of turbine-inlet temperature ratio with power extraction and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 1.35.



(b) Corrected engine speed, rated.

Figure 1. - Continued. Variation of turbine-inlet temperature ratio with power extraction and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 1.35.

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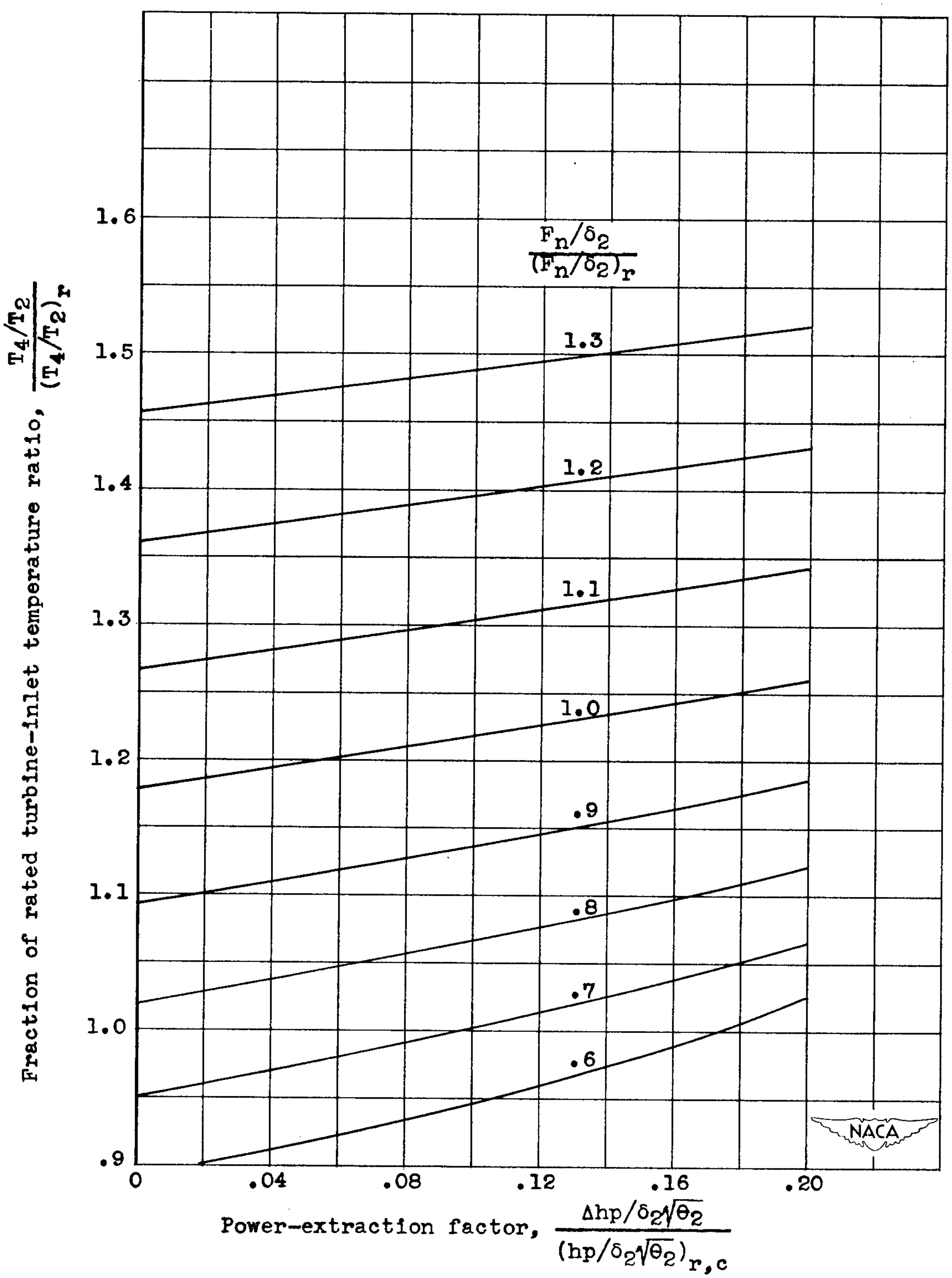
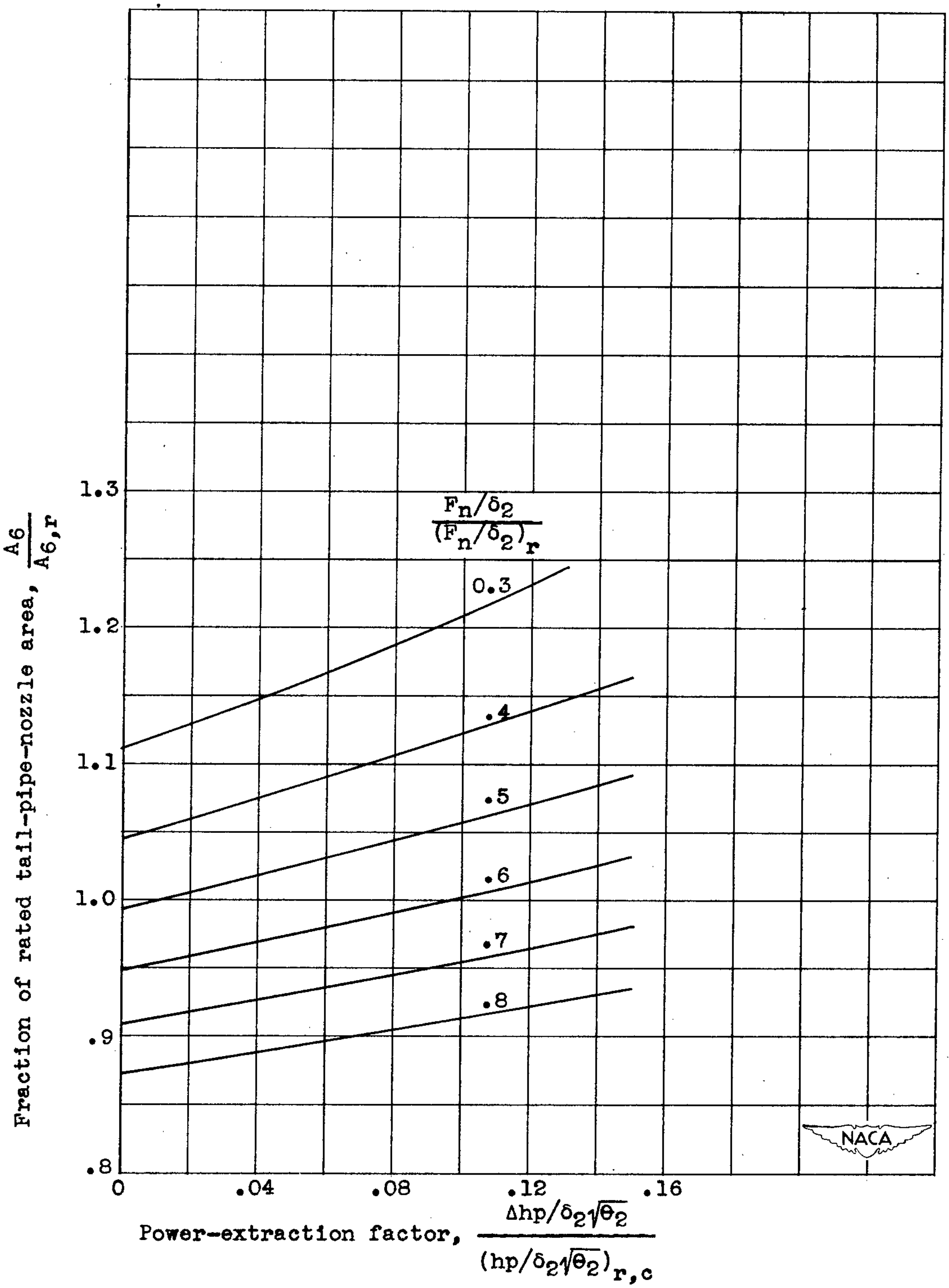


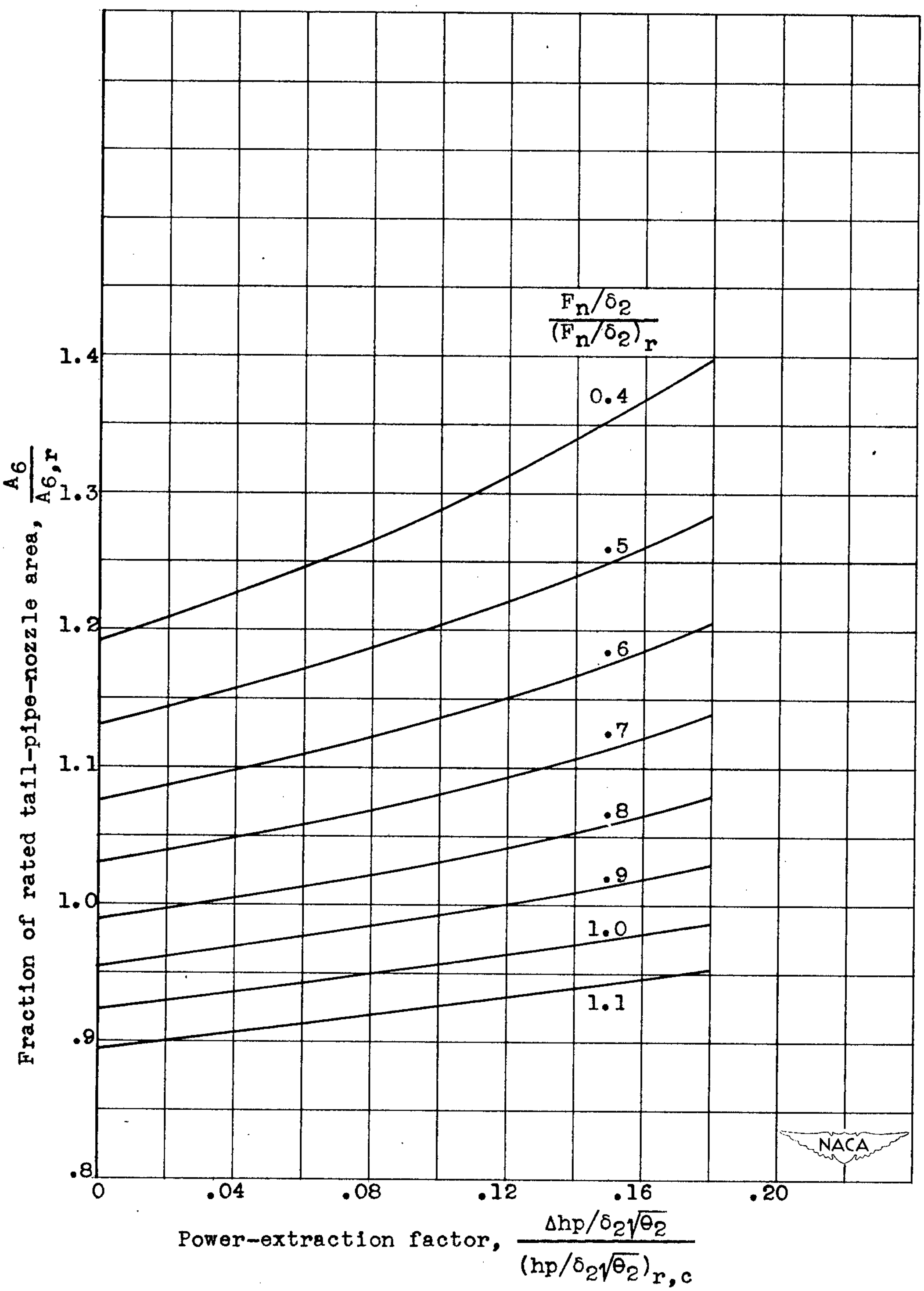
(c) Corrected engine speed, 1.1 rated.

Figure 1. - Concluded. Variation of turbine-inlet temperature ratio with power extraction and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 1.35.



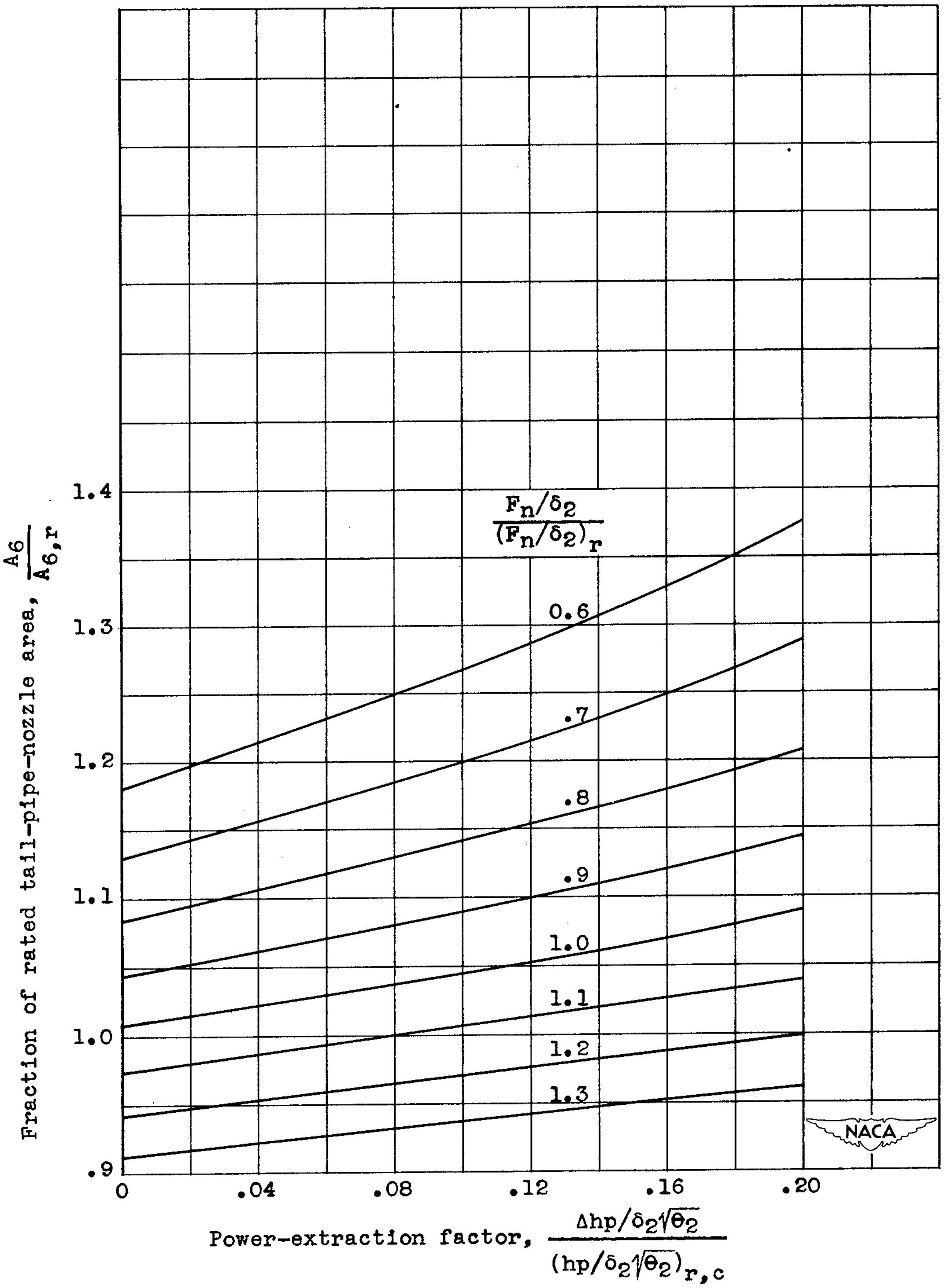
(a) Corrected engine speed, 0.9 rated.

Figure 2. - Variation of tail-pipe-nozzle area with power extraction and thrust for ram pressure ratio of 1.35.



(b) Corrected engine speed, rated.

Figure 2. - Continued. Variation of tail-pipe-nozzle area with power extraction and thrust for ram pressure ratio of 1.35.



(c) Corrected engine speed, 1.1 rated.

Figure 2. - Concluded. Variation of tail-pipe-nozzle area with power extraction and thrust for ram pressure ratio of 1.35.

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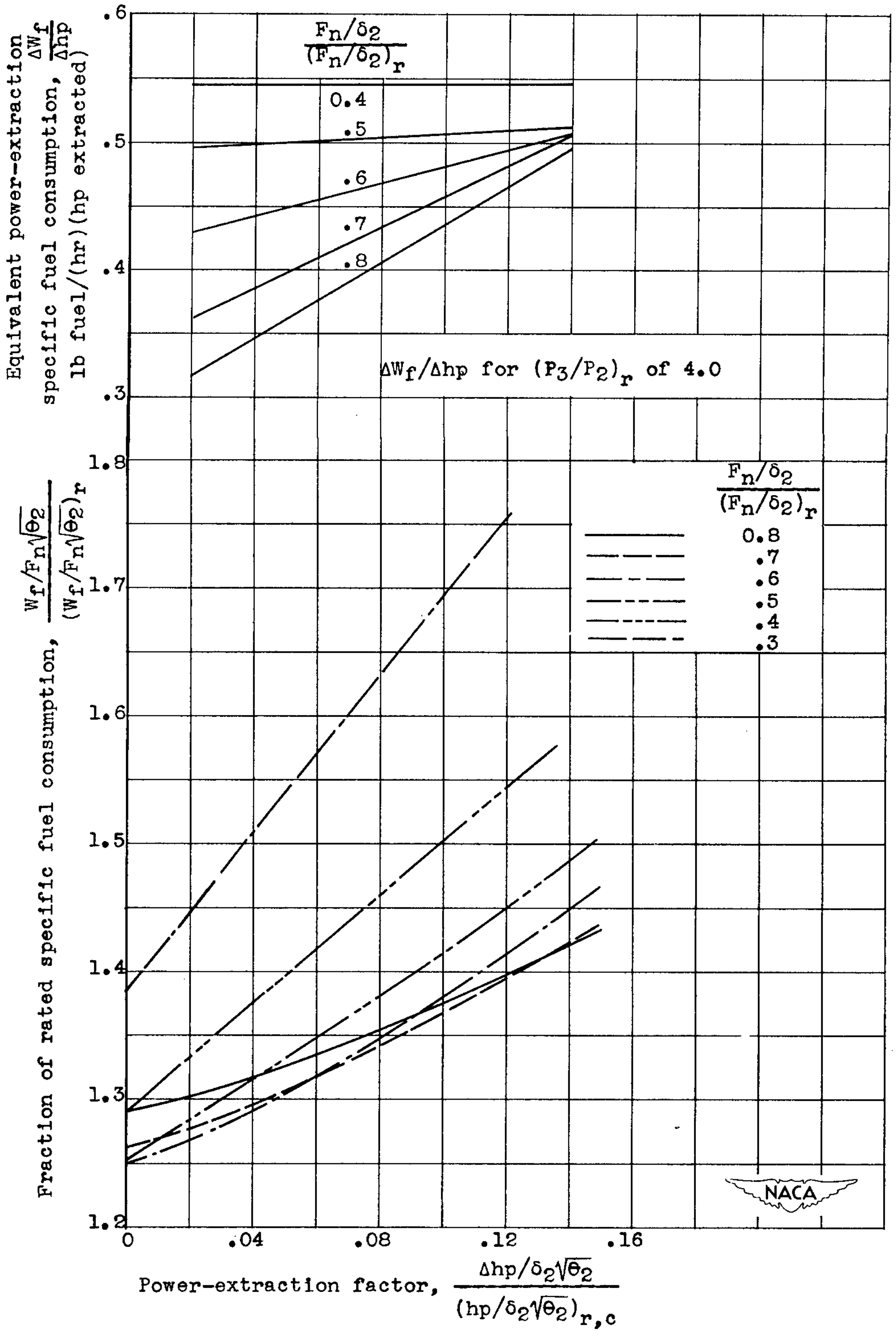
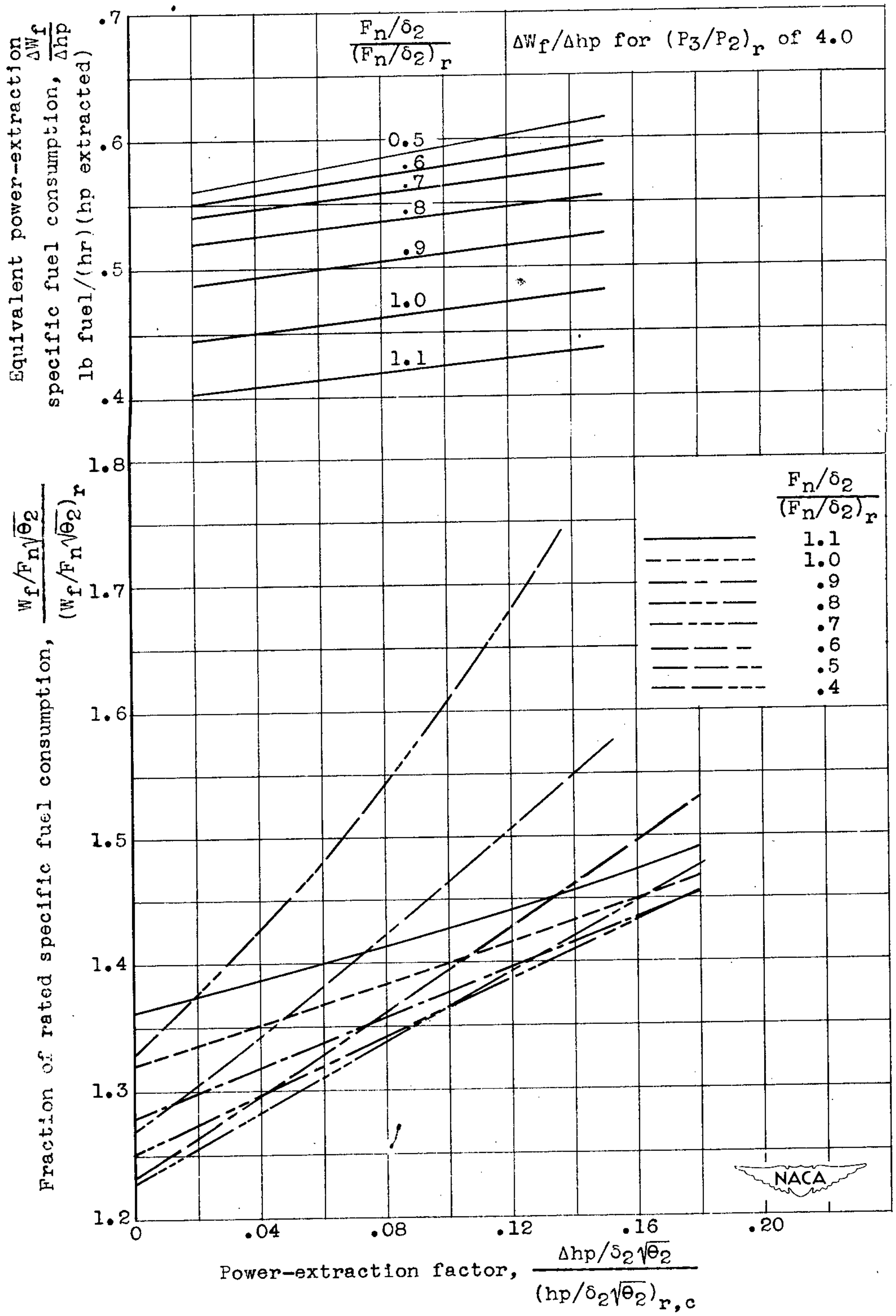


(a) Corrected engine speed, 0.9 rated.

Figure 3. - Variation of specific fuel consumption with power extraction and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 1.35.



(b) Corrected engine speed, rated.

Figure 3. - Continued. Variation of specific fuel consumption with power extraction and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 1.35.

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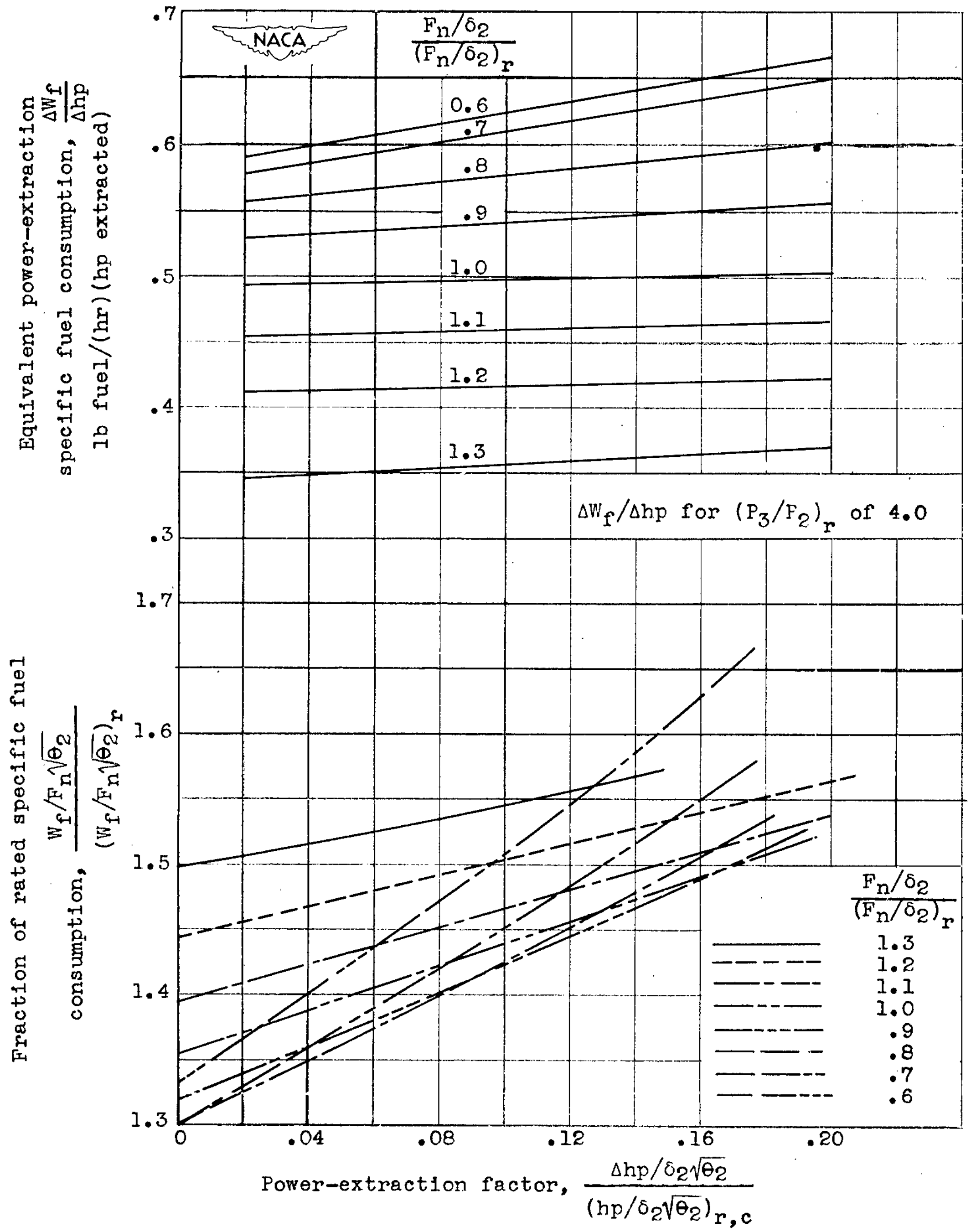
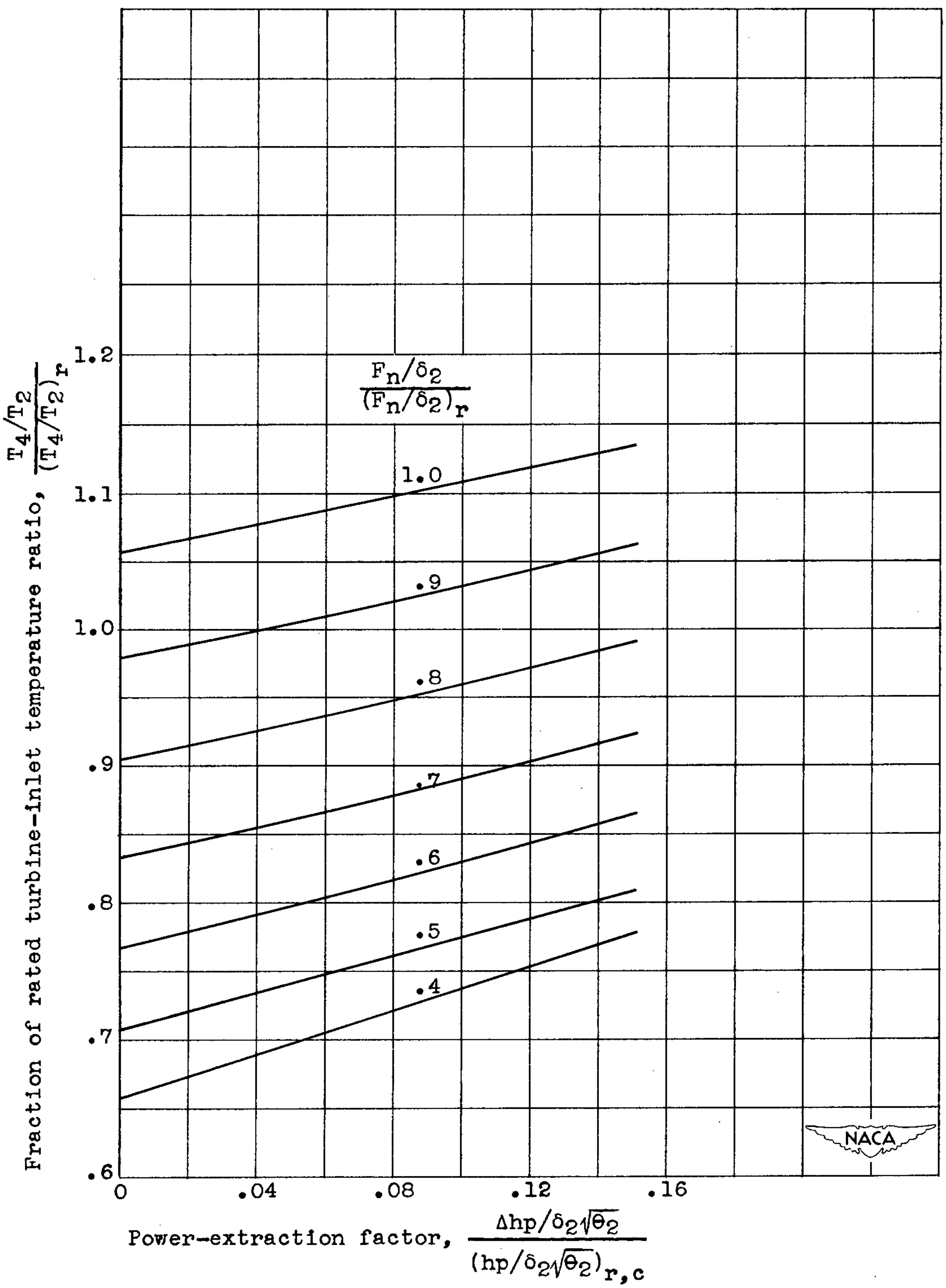


(c) Corrected engine speed, 1.1 rated.

Figure 3. - Concluded. Variation of specific fuel consumption with power extraction and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 1.35.



(a) Corrected engine speed, 0.9 rated.

Figure 4. - Variation of turbine-inlet temperature ratio with power extraction and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 0.99.

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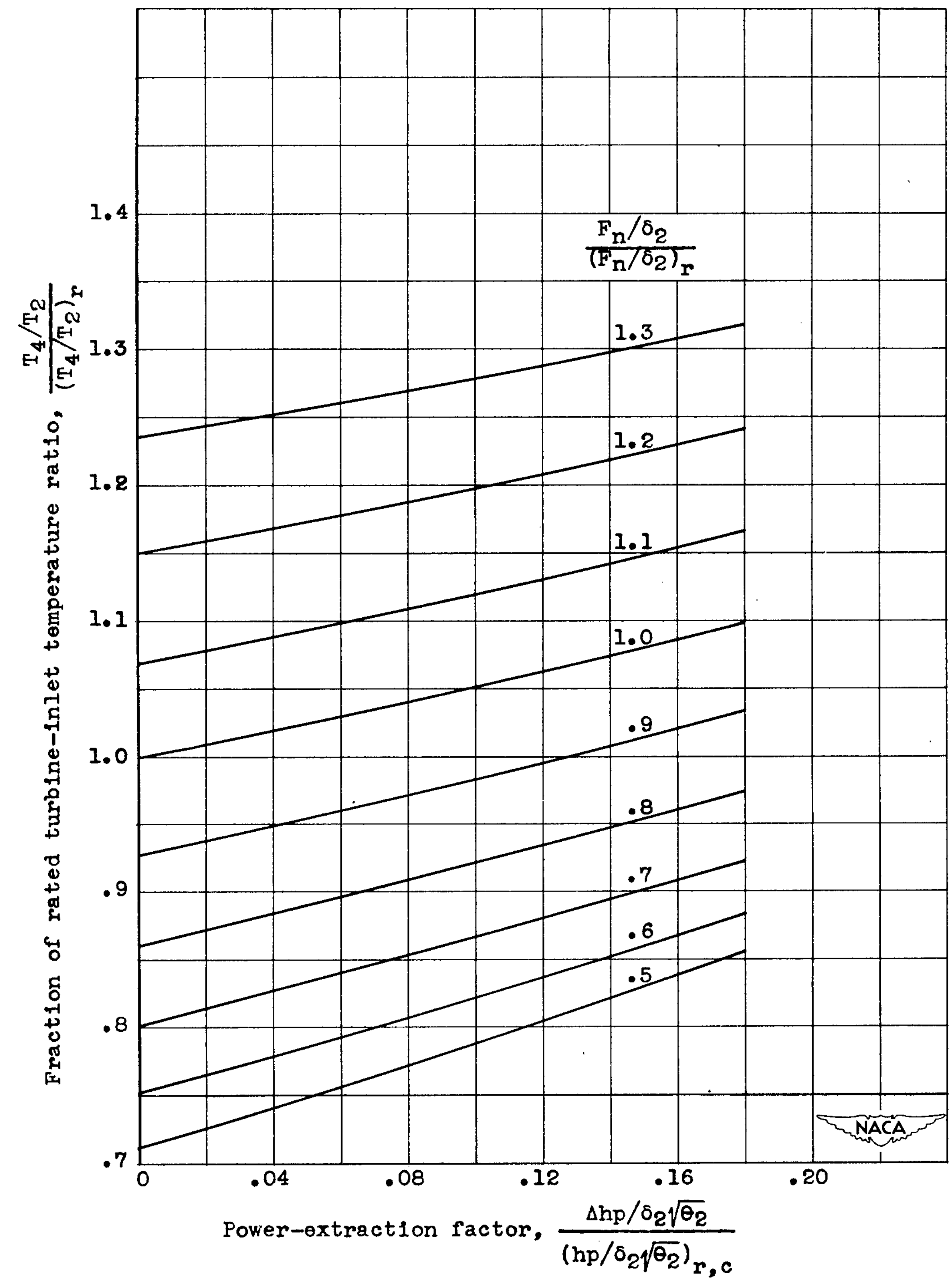
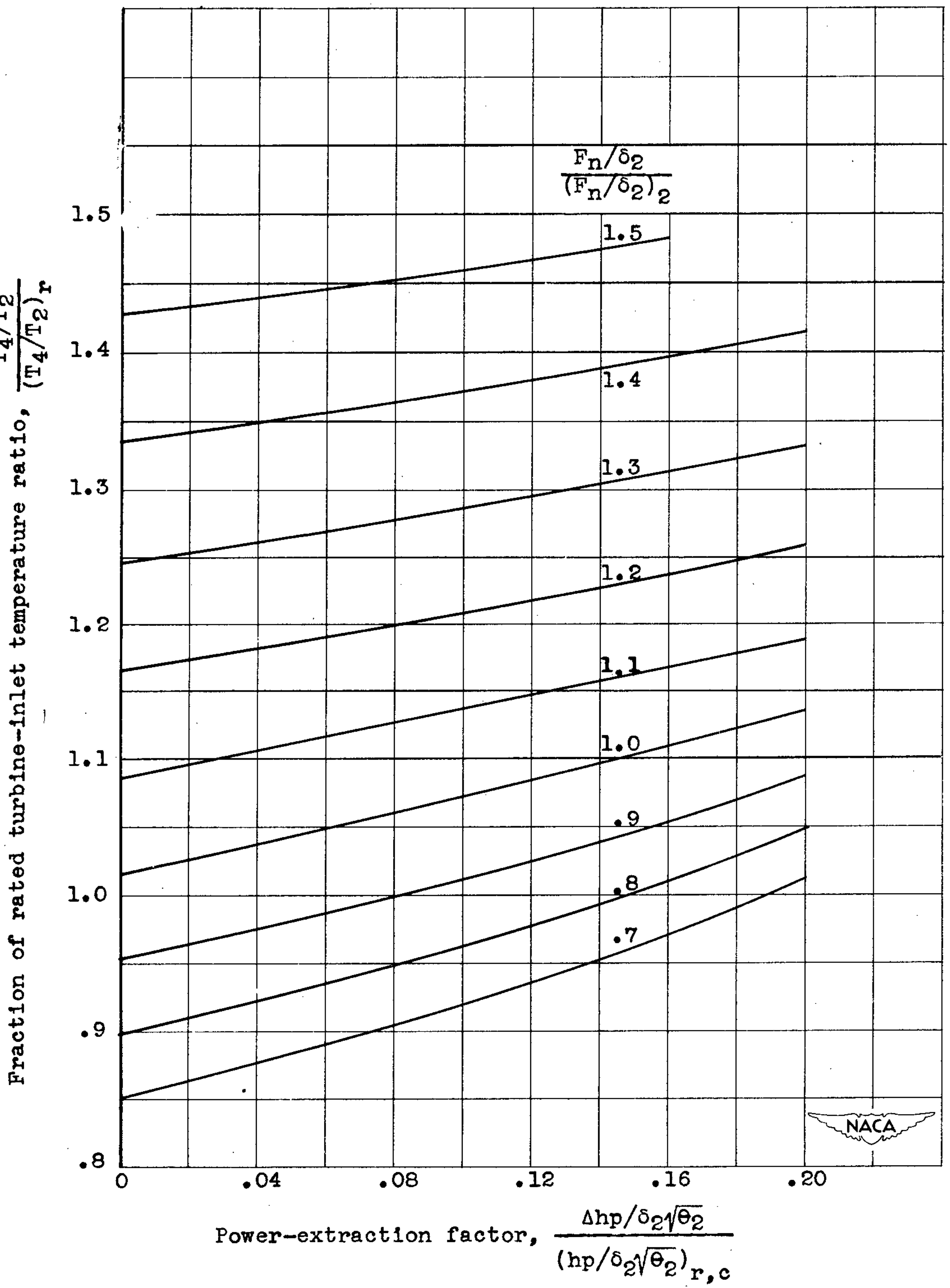


(b) Corrected engine speed, rated.

Figure 4. - Continued. Variation of turbine-inlet temperature ratio with power extraction and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 0.99.



(c) Corrected engine speed, 1.1 rated.

Figure 4. - Concluded. Variation of turbine-inlet temperature ratio with power extraction and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 0.99.

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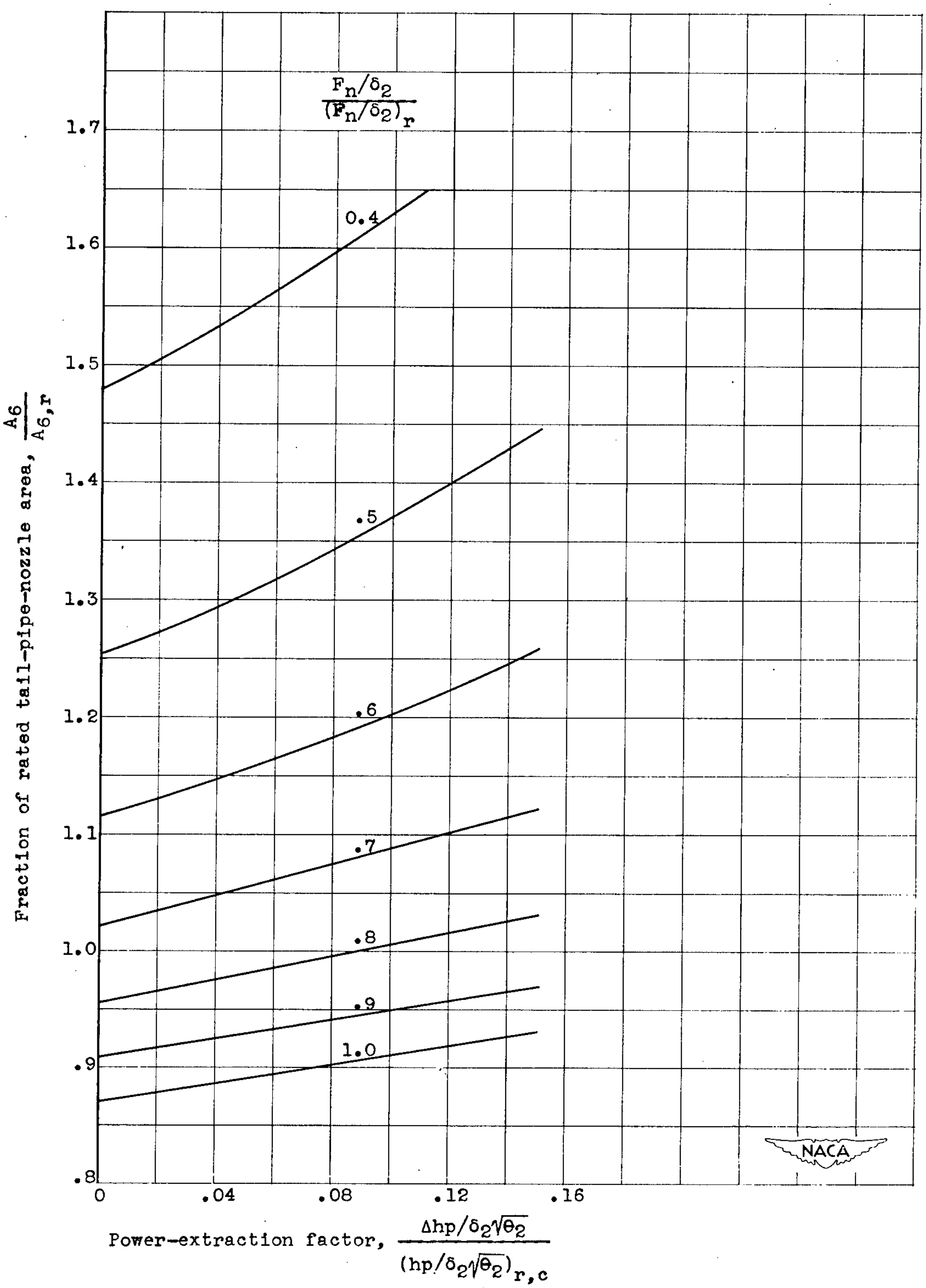
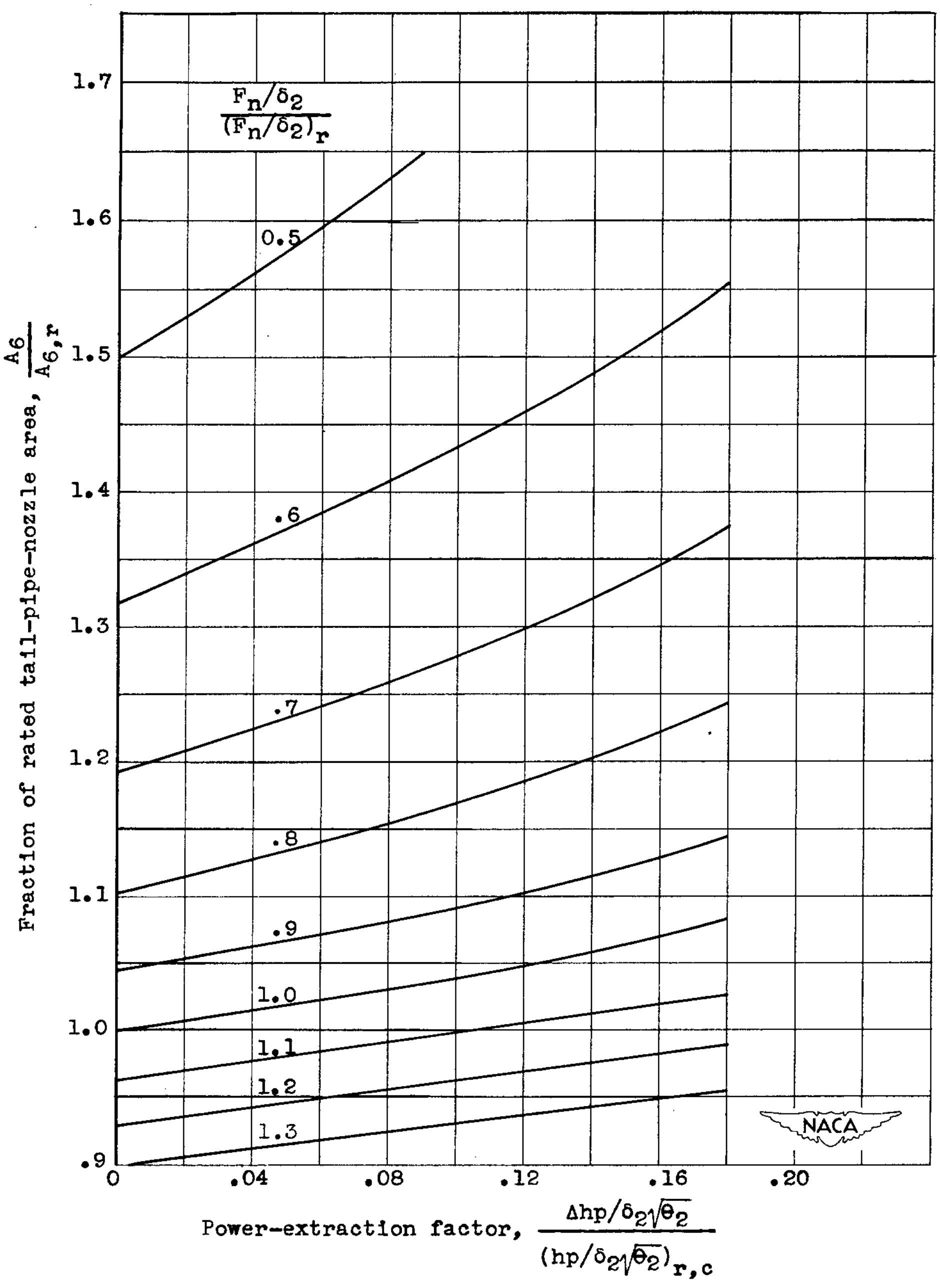


(a) Corrected engine speed, 0.9 rated.

Figure 5. - Variation of tail-pipe-nozzle area with power extraction and thrust for ram pressure ratio of 0.99.



(b) Corrected engine speed, rated.

Figure 5. - Continued. Variation of tail-pipe-nozzle area with power extraction and thrust for ram pressure ratio of 0.99.

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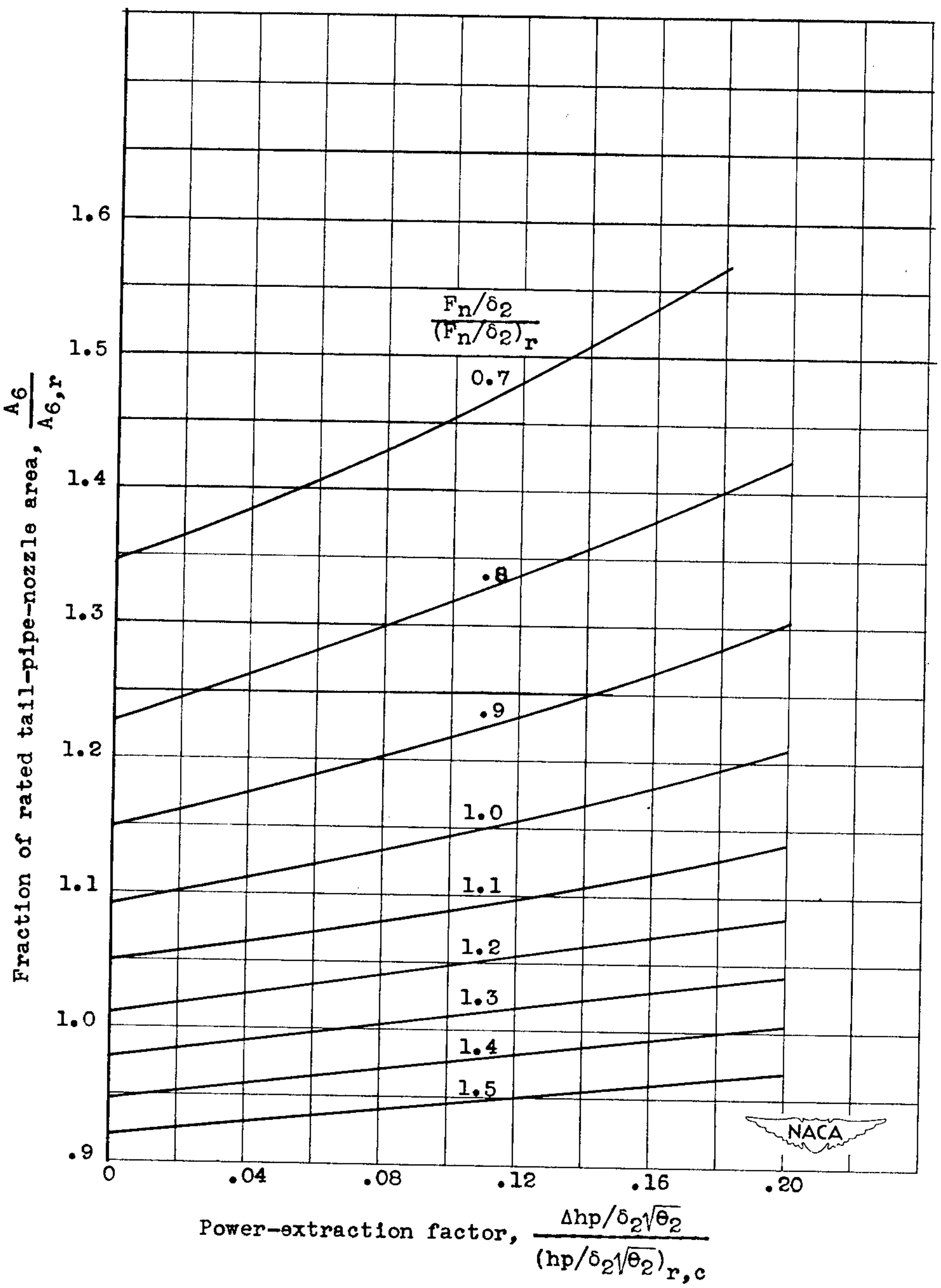
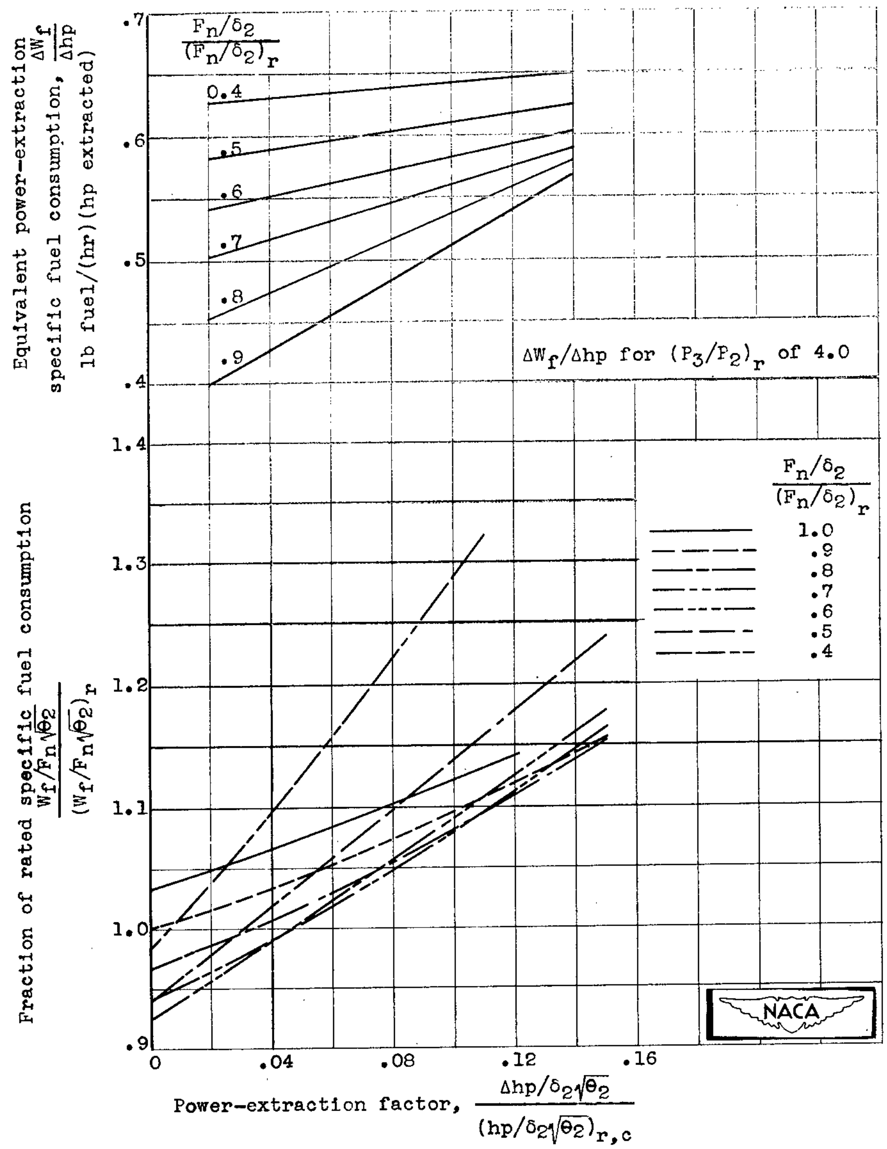


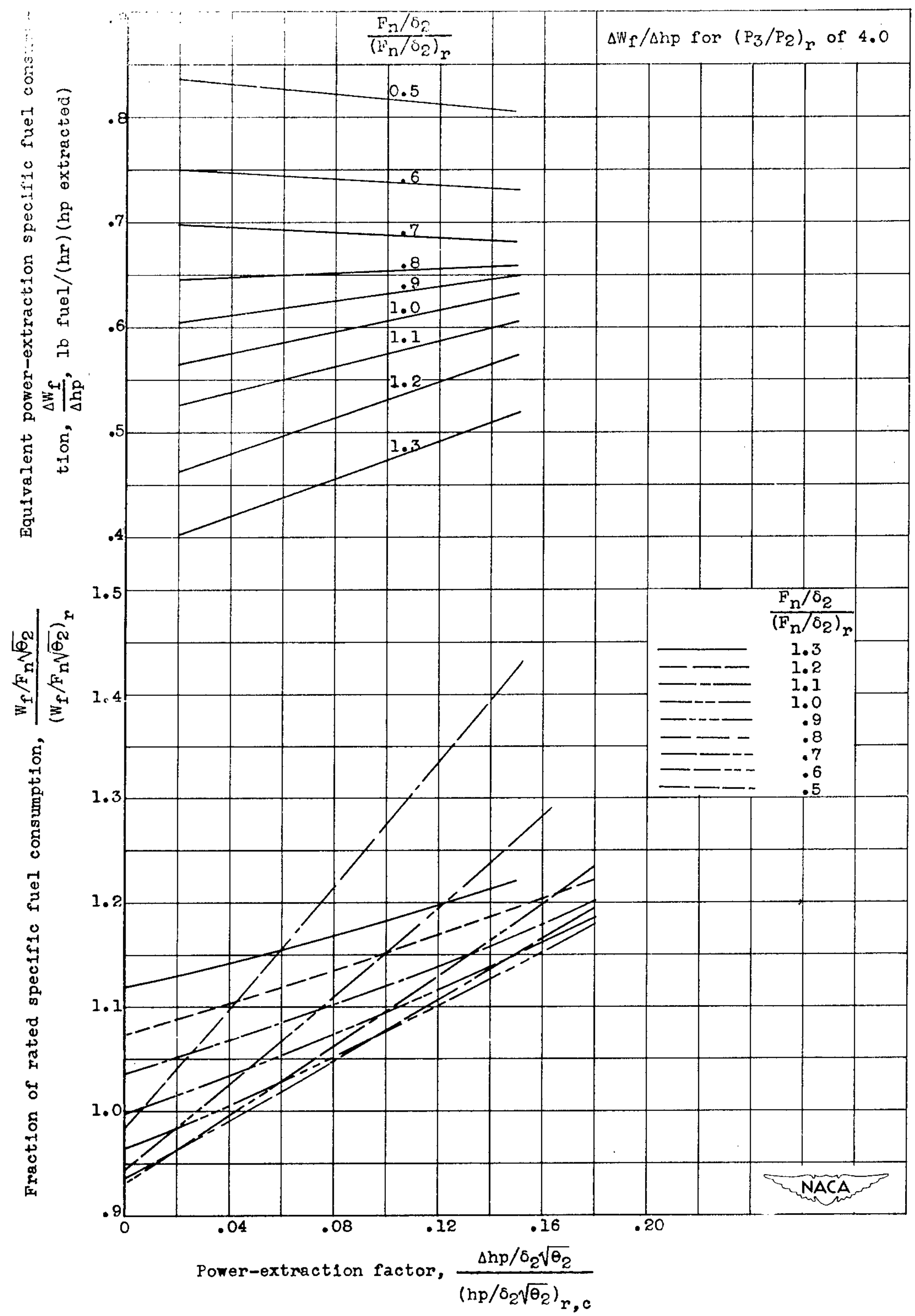
(c) Corrected engine speed, 1.1 rated.

Figure 5. - Concluded. Variation of tail-pipe-nozzle area with power extraction and thrust for ram pressure ratio of 0.99.



(a) Corrected engine speed, 0.9 rated.

Figure 6. - Variation of specific fuel consumption with power extraction and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 0.99.



(b) Corrected engine speed, rated.

Figure 6. - Continued. Variation of specific fuel consumption with power extraction and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 0.99.

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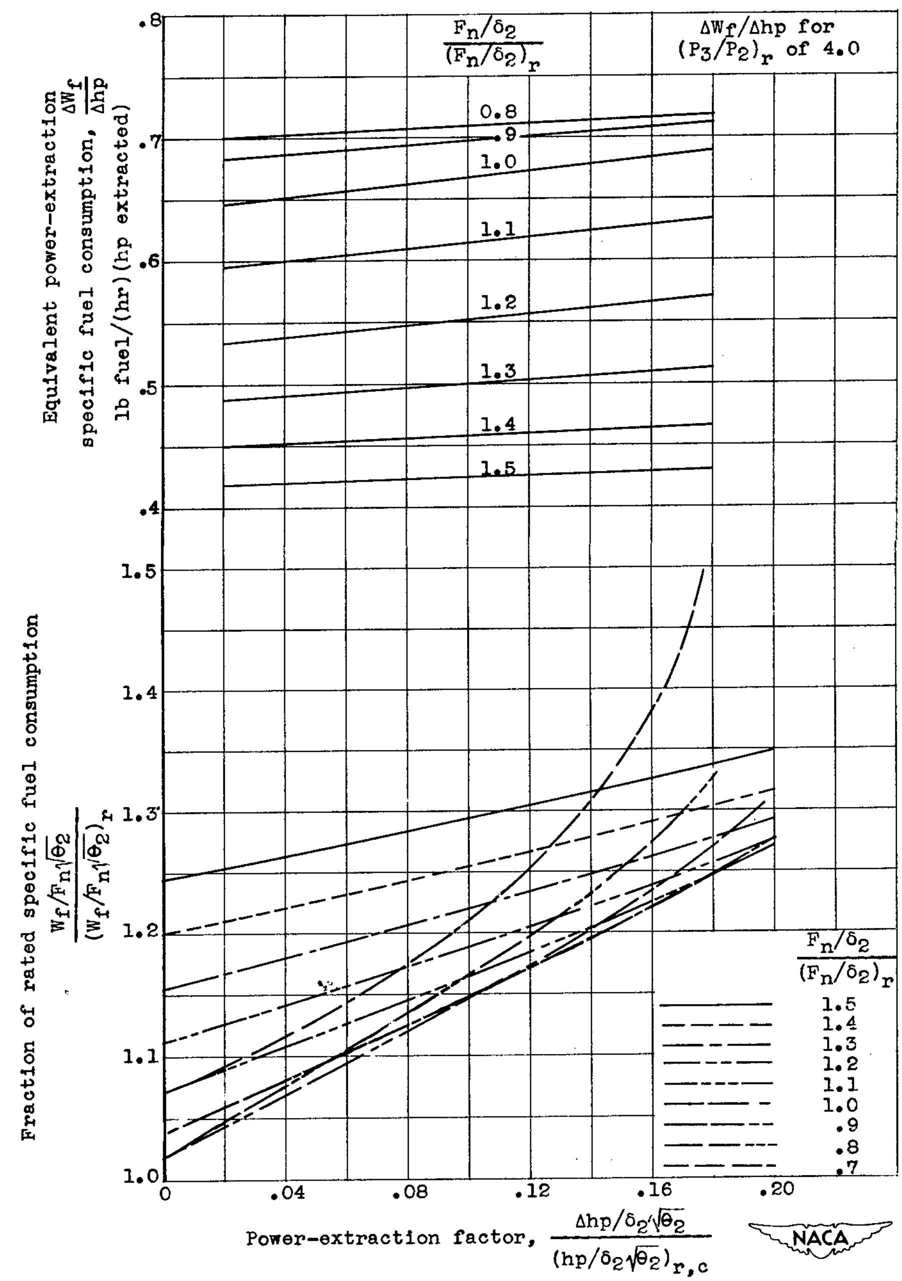

(c) Corrected engine speed, 1.1 rated.

Figure 6. - Concluded. Variation of specific fuel consumption with power extraction and thrust for variable-area tail-pipe nozzle and ram pressure ratio of 0.99.

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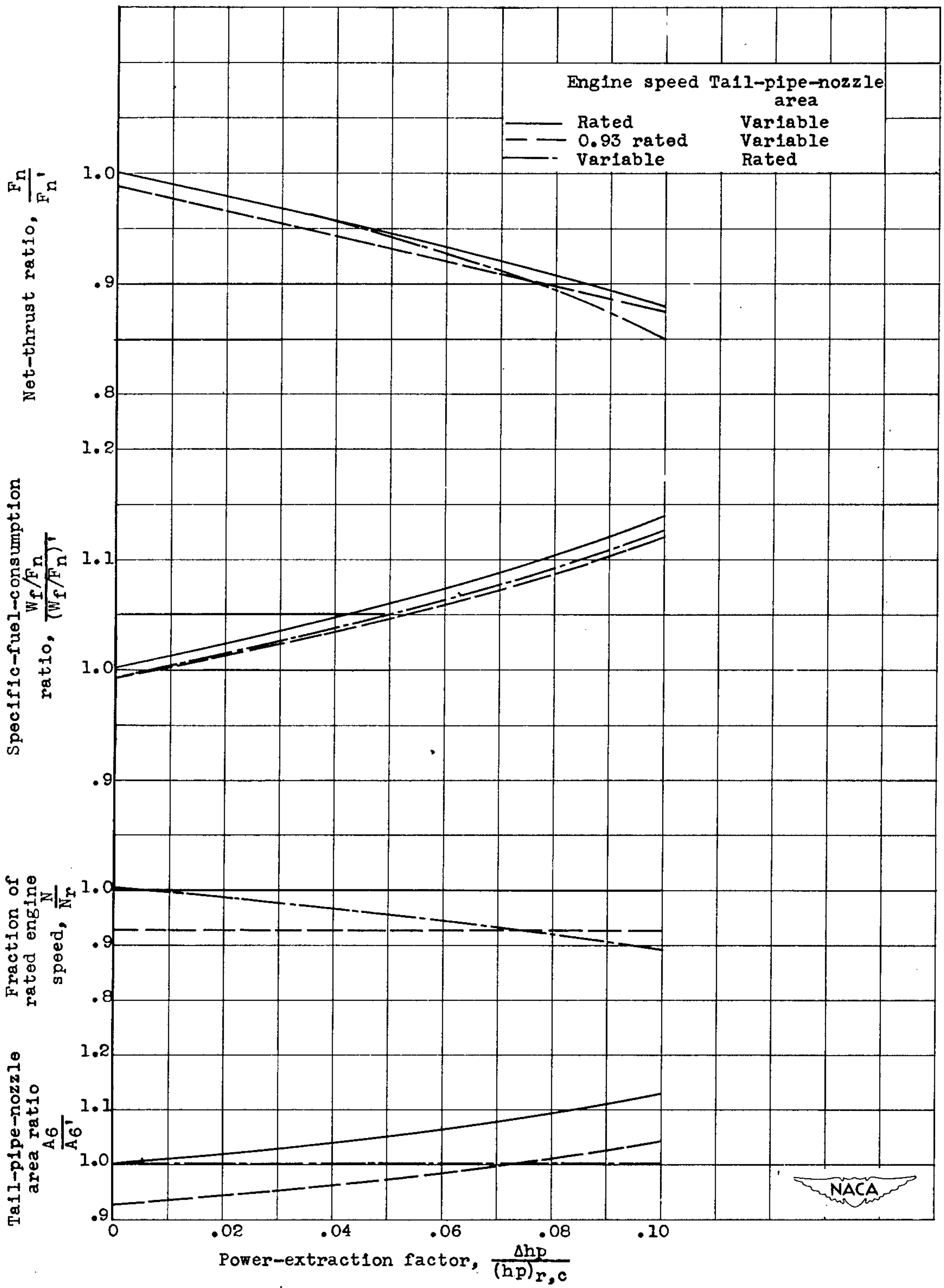
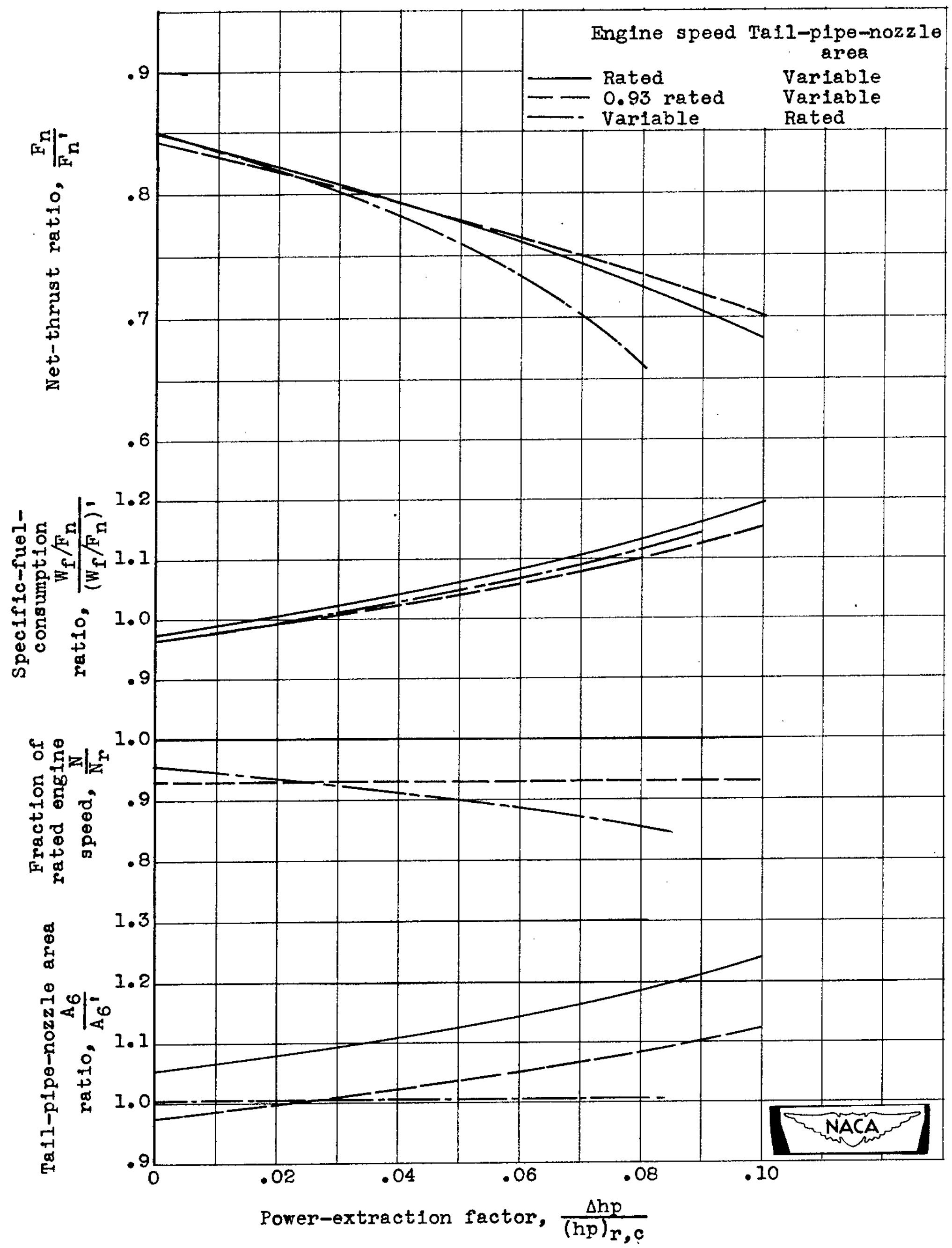


(a) Rated turbine-inlet temperature.

Figure 7. - Effect of shaft-power extraction on engine performance for variable and constant tail-pipe-nozzle area operation. Altitude, 20,000 feet; Mach number, 0.7.



(b) 0.9 rated turbine-inlet temperature.

Figure 7. - Concluded. Effect of shaft-power extraction on engine performance for variable and constant tail-pipe-nozzle area operation. Altitude, 20,000 feet; Mach number, 0.7.

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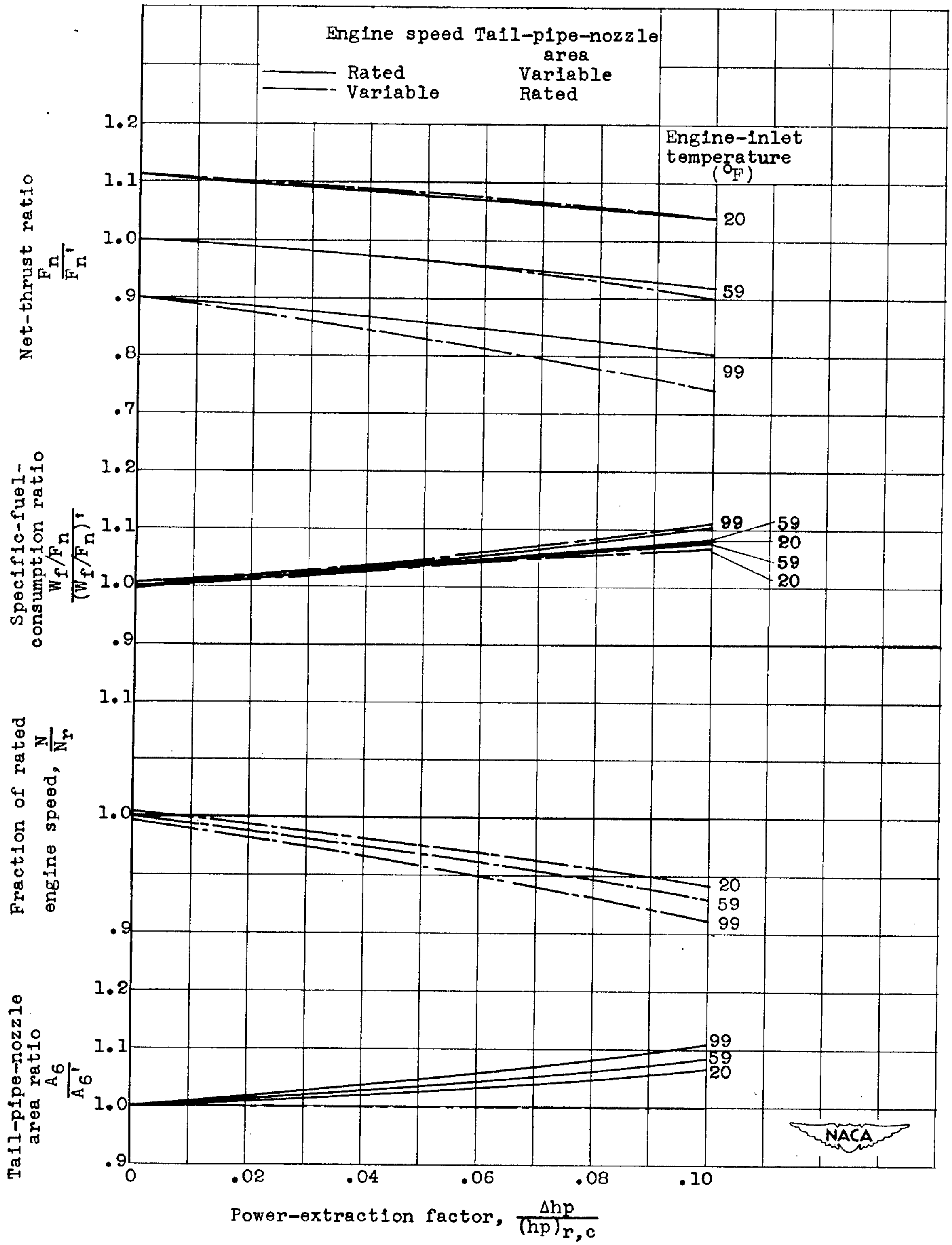

Figure 8. - Effect of shaft-power extraction and engine-inlet temperature on sea-level static engine performance for variable and constant tail-pipe-nozzle area operation at rated turbine-inlet temperature.

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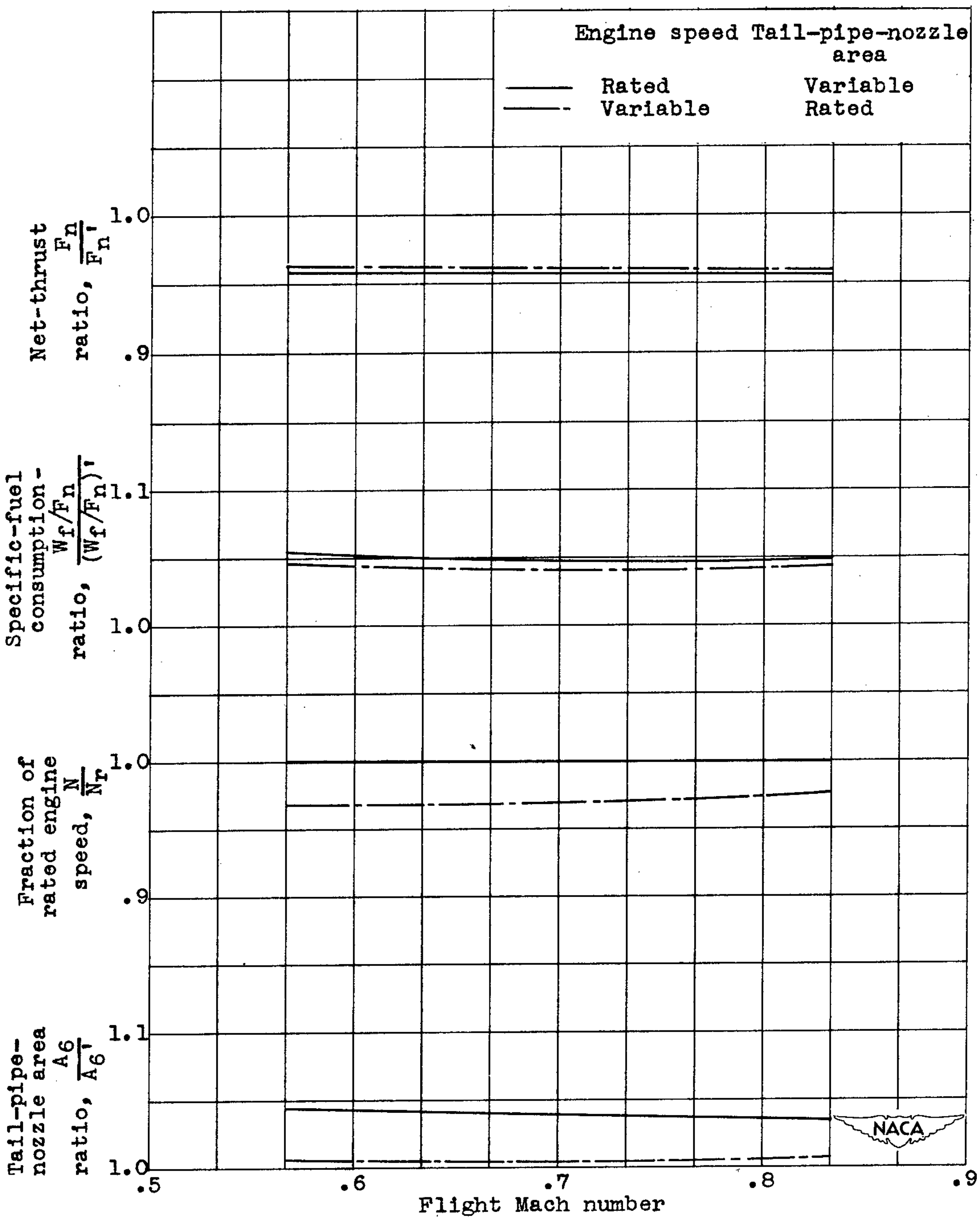

Figure 9. - Effect of flight Mach number on engine performance for variable and constant tail-pipe-nozzle area operation and power-extraction factor of 0.04. Rated turbine-inlet temperature; altitude, 20,000 feet.

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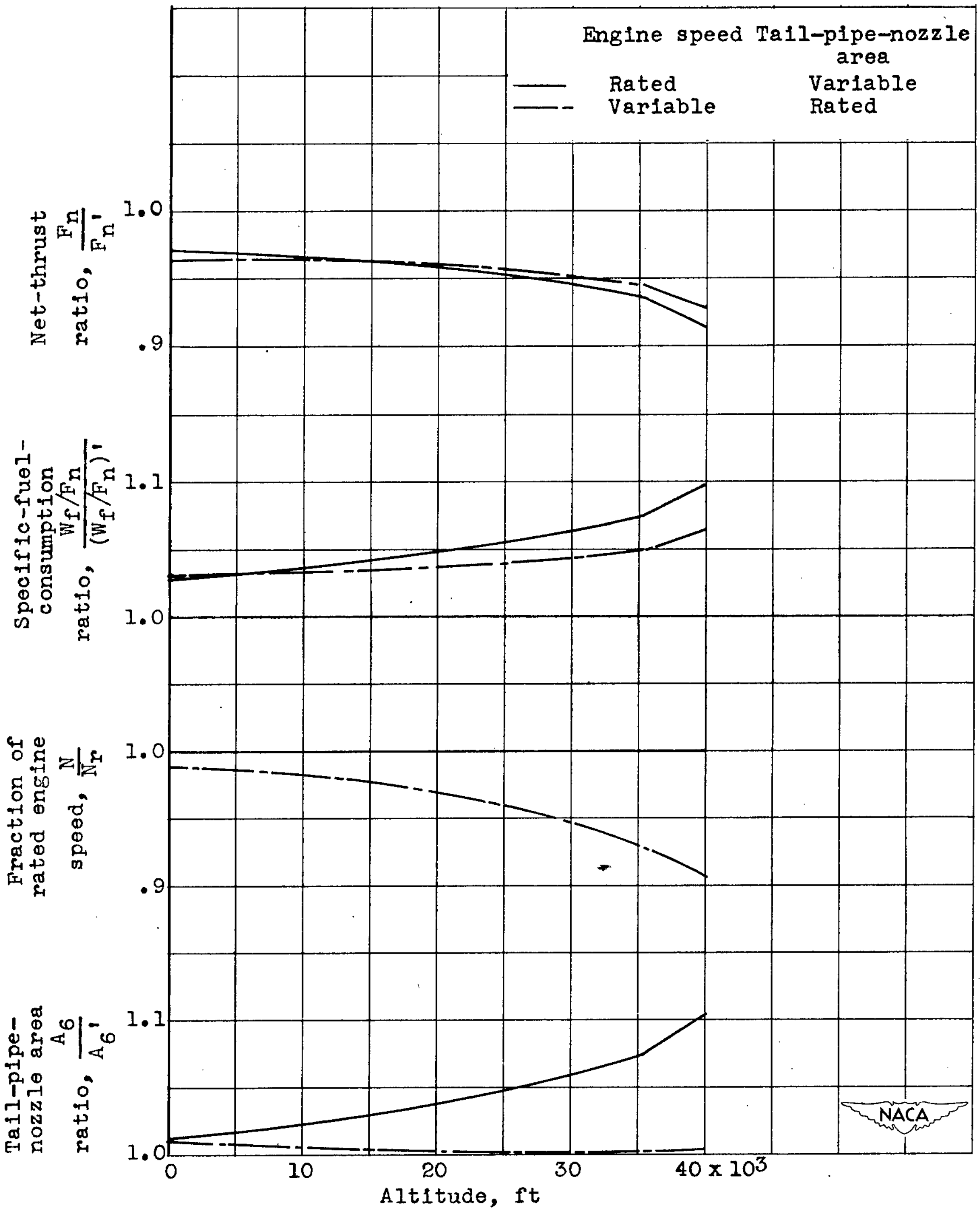

Figure 10. - Effect of altitude on engine performance for variable and constant tail-pipe-nozzle area operation and power-extraction factor of 0.04. Rated turbine-inlet temperature; Mach number, 0.7.

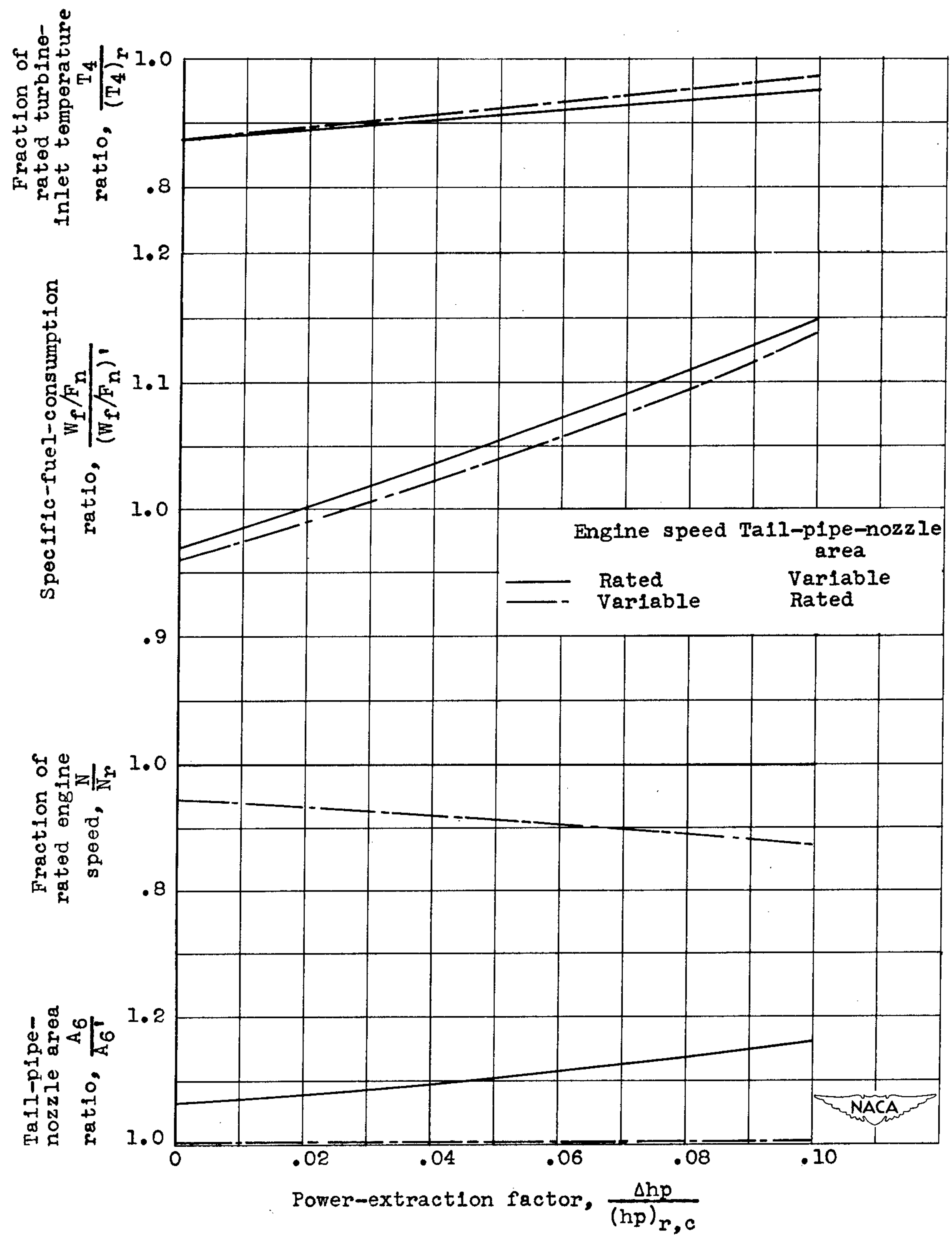

Figure 11. - Effect of shaft-power extraction on engine performance for variable and constant tail-pipe-nozzle area operation at constant net-thrust ratio of 0.80. Altitude, 20,000 feet; Mach number, 0.7.

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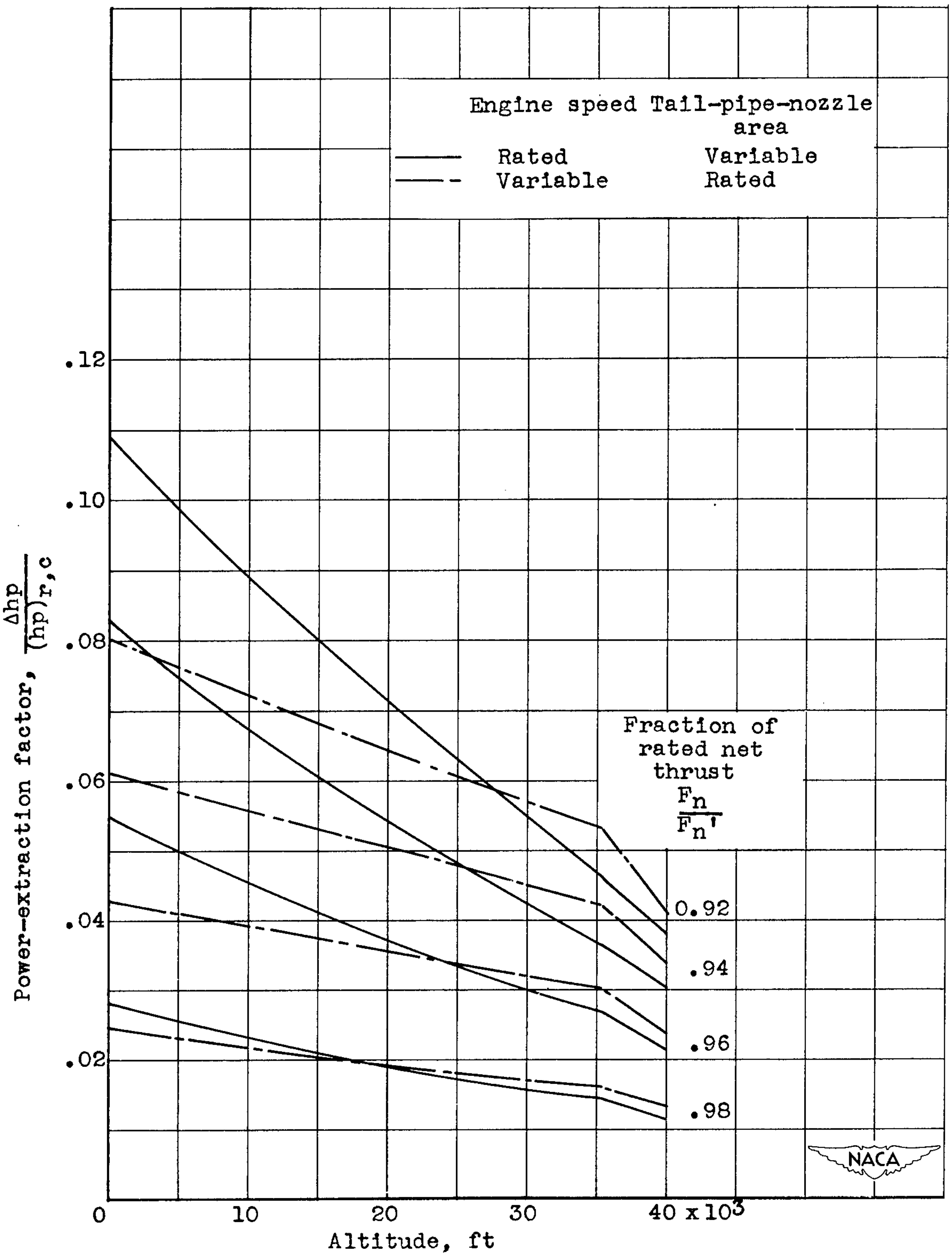

Figure 12. - Variation of maximum permissible shaft-power extraction with altitude and thrust. Rated turbine-inlet temperature; Mach number, 0.7.

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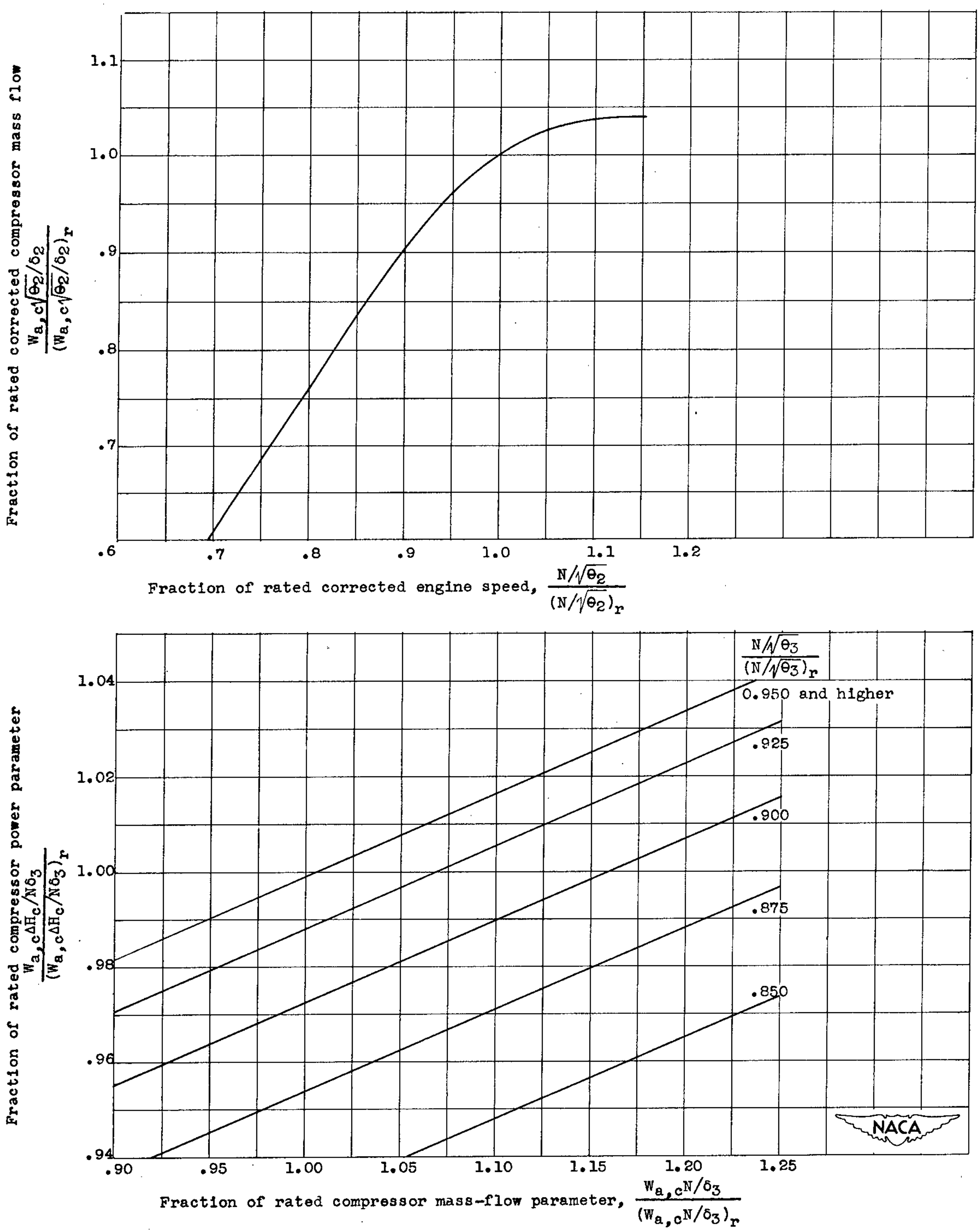

Figure 13. - Idealized axial-flow compressor characteristics.

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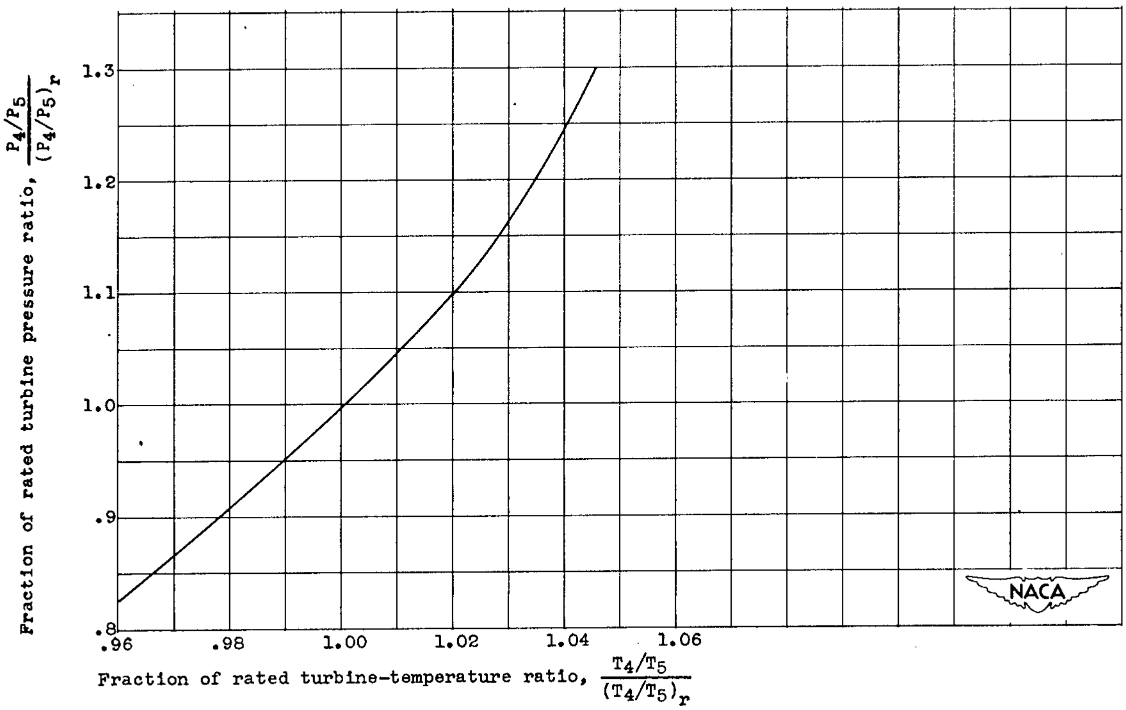

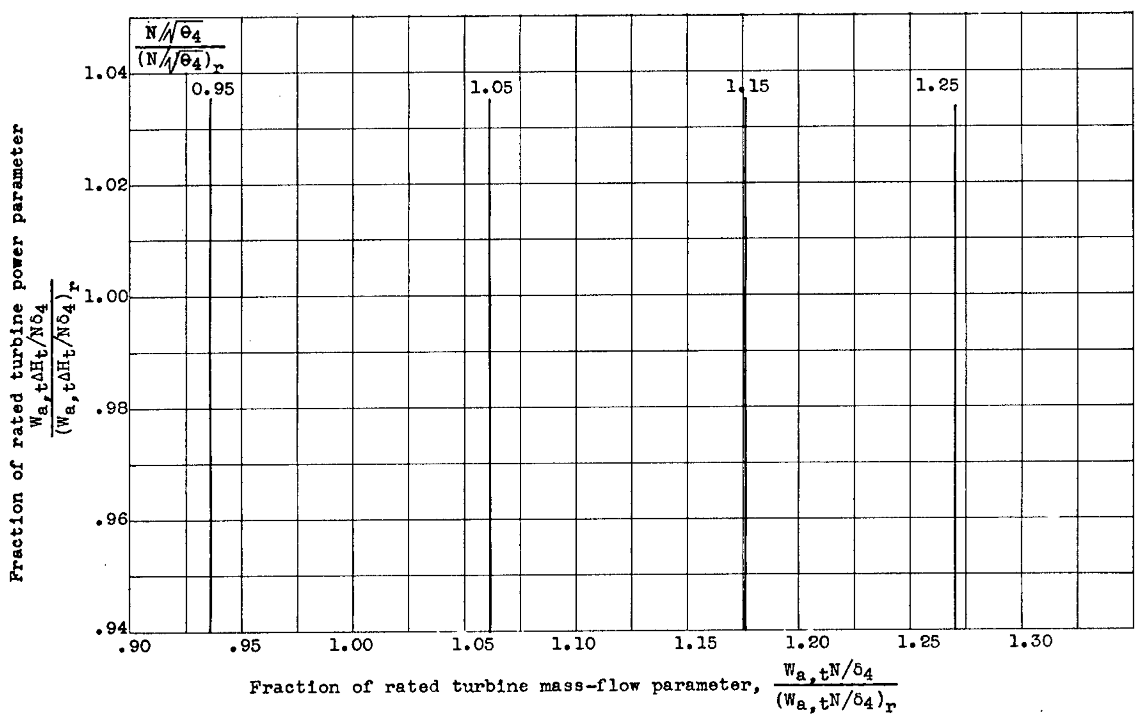

Figure 14. - Idealized turbine characteristics.

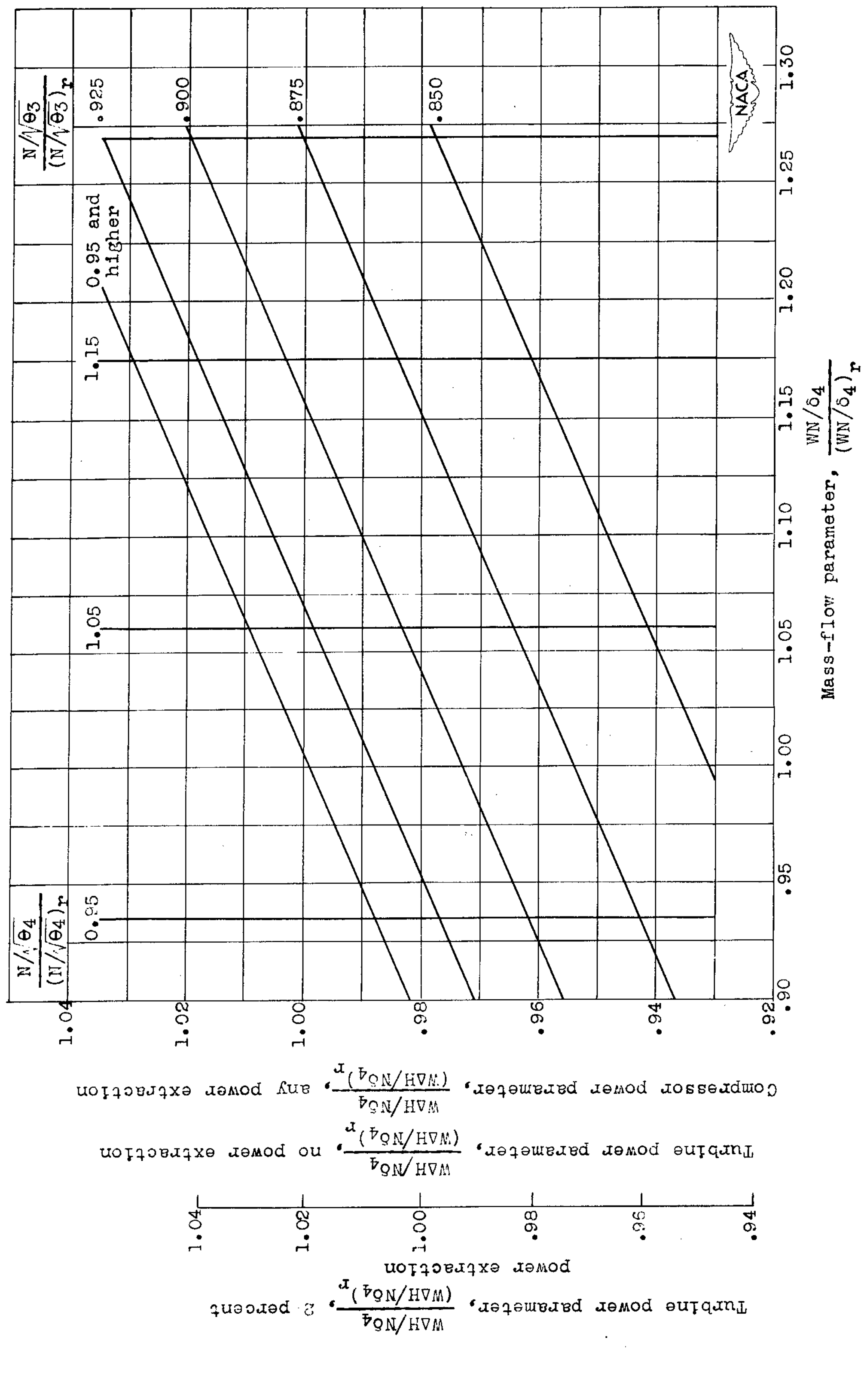

Figure 15. - Compressor and turbine matching chart.

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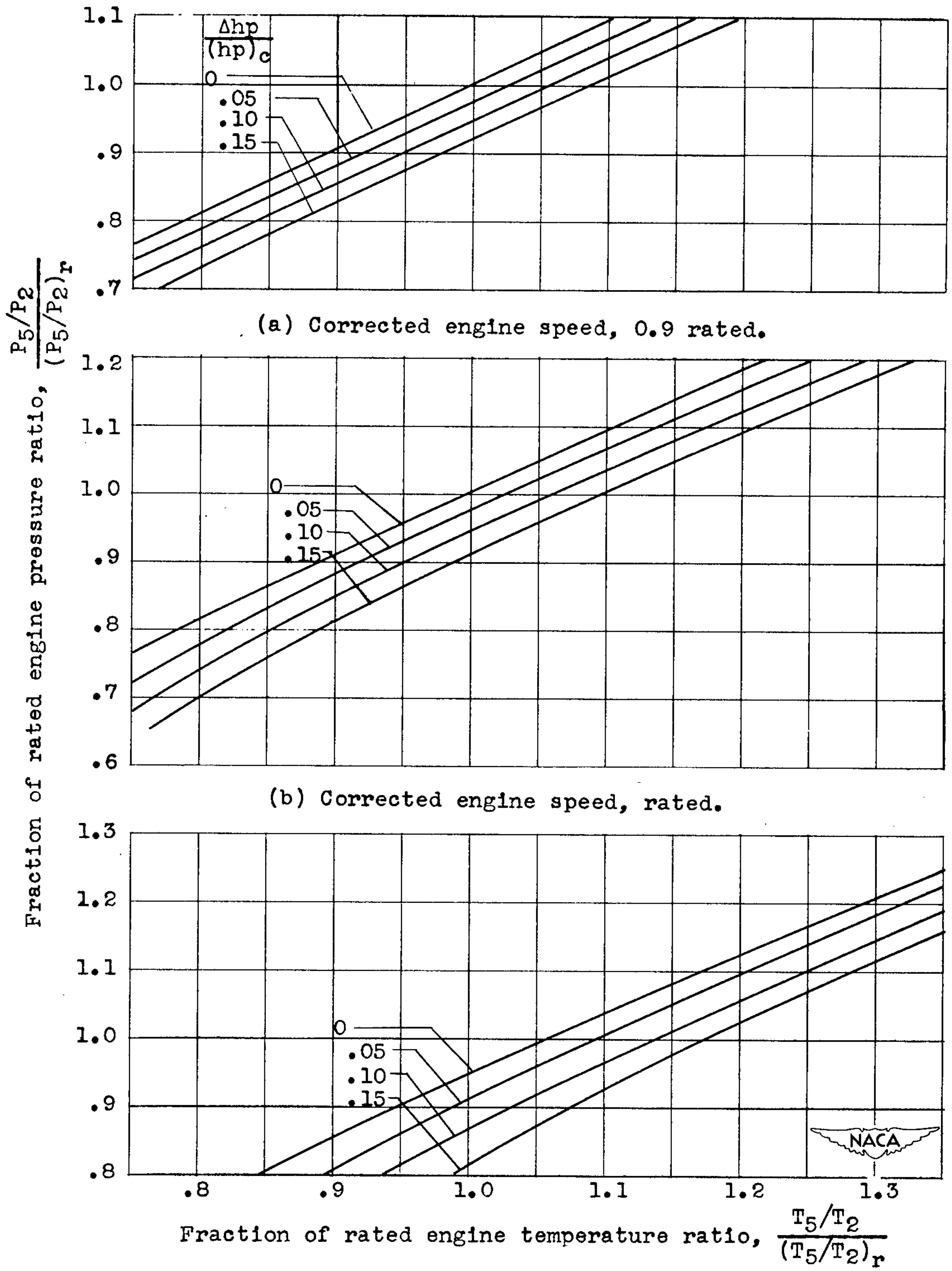

(c) Corrected engine speed, 1.1 rated.

Figure 16. - Variation of engine pressure ratio with engine temperature ratio and shaft-power extraction for three engine speeds.

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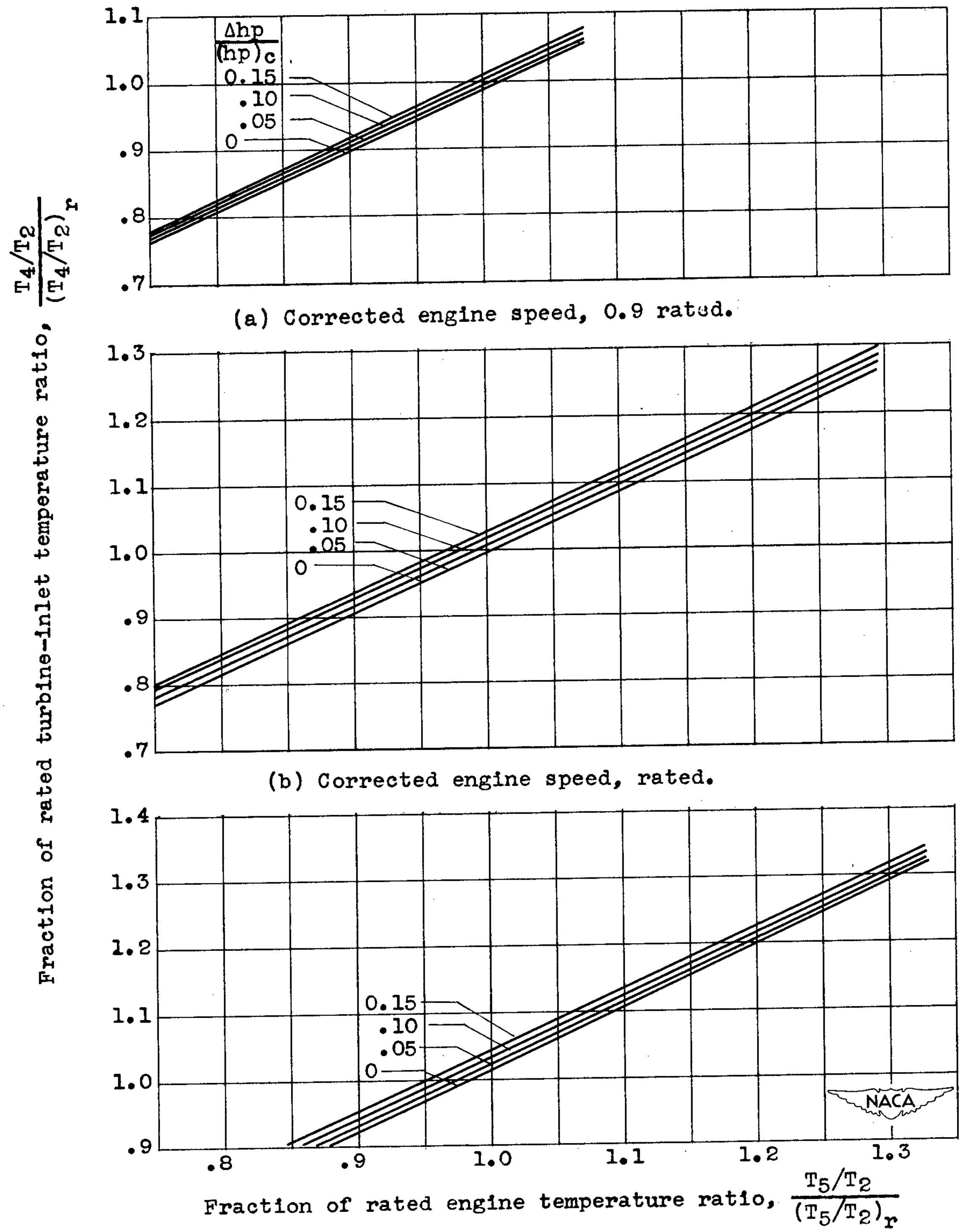
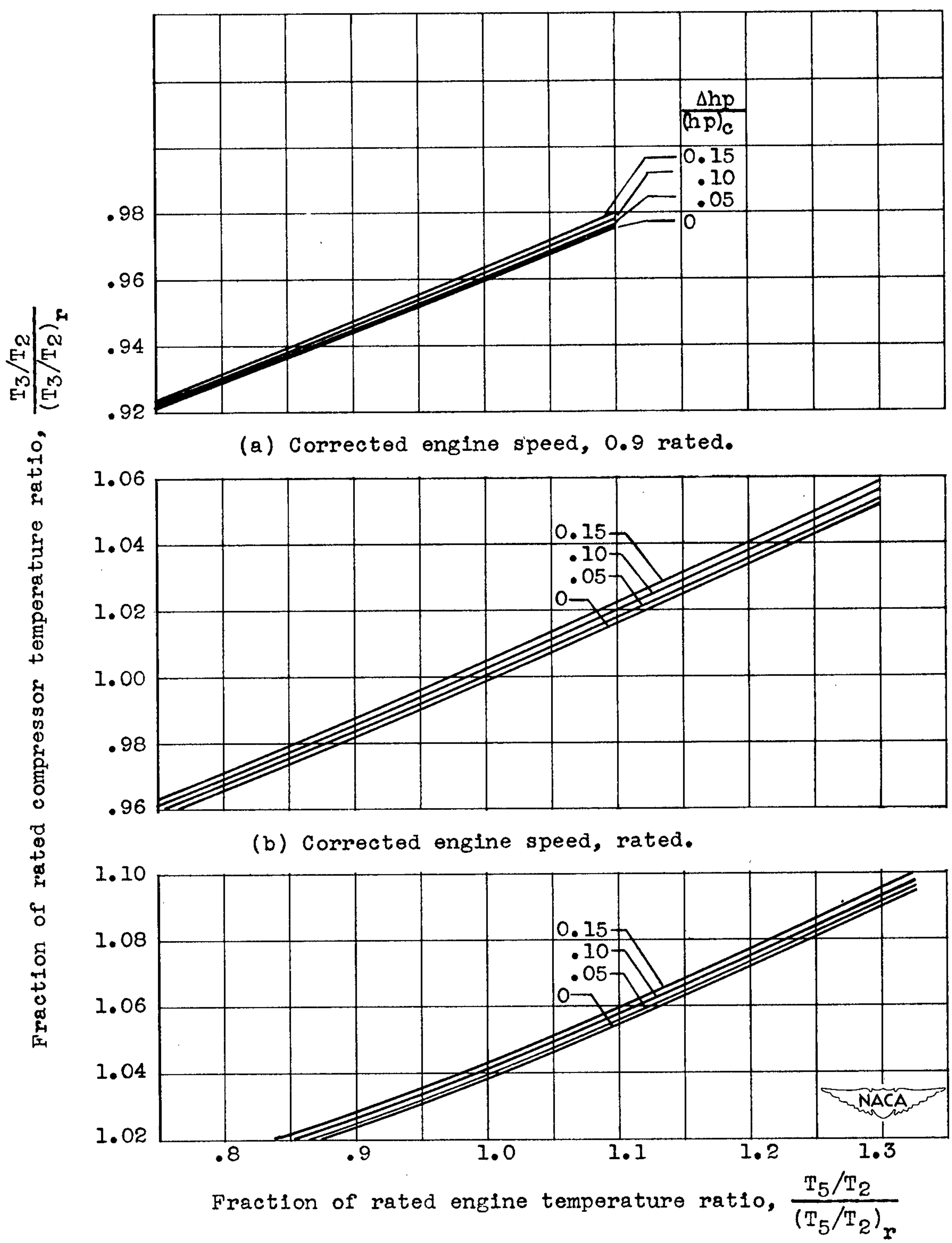


(c) Corrected engine speed, 1.1 rated.

Figure 17. - Variation of turbine-inlet temperature ratio with engine temperature ratio and shaft-power extraction for three engine speeds.



(c) Corrected engine speed, 1.1 rated.

Figure 18. - Variation of compressor temperature ratio with engine temperature ratio and shaft-power extraction for three engine speeds.

Engines, Turbojet 3.1.3

Effect of Heat and Power Extraction on Turbojet-Engine Performance. III - Analytical Determination of Effects of Shaft-Power Extraction.

By Stanley L. Koutz, Reece V. Hensley, and Frank E. Rom

NACA TN 2202

October 1950

(Abstract on Reverse Side)

Booster Systems, Auxiliary - Gas Turbines 3.3.2

Effect of Heat and Power Extraction on Turbojet-Engine Performance. III - Analytical Determination of Effects of Shaft-Power Extraction.

By Stanley L. Koutz, Reece V. Hensley, and Frank E. Rom

NACA TN 2202

October 1950

(Abstract on Reverse Side)

Compressors - Matching 3.6.3

Effect of Heat and Power Extraction on Turbojet-Engine Performance. III - Analytical Determination of Effects of Shaft-Power Extraction.

By Stanley L. Koutz, Reece V. Hensley, and Frank E. Rom

NACA TN 2202

October 1950

(Abstract on Reverse Side)

Turbines - Matching 3.7.4

Effect of Heat and Power Extraction on Turbojet-Engine Performance. III - Analytical Determination of Effects of Shaft-Power Extraction.

By Stanley L. Koutz, Reece V. Hensley, and Frank E. Rom

NACA TN 2202

October 1950

(Abstract on Reverse Side)

Abstract

Generalized working charts, prepared by matching experimentally determined component characteristics of a typical axial-flow-type turbojet engine, are presented for determining the effect of shaft-power extraction on engine performance.

The effects of shaft-power extraction on engine performance under several representative modes of engine operation are presented by use of the generalized working charts. Variation in the effect of shaft-power extraction with altitude, flight Mach number, and engine-inlet temperature is considered.

Abstract

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